Efficient, Wide Band, Integrated Lightwave Devices Transmitters for RF-Transmissions

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Integrated RF-Photonic Transmitters

OBJECTIVES:

Design and fabricate low-V_π integrated RF-photonic transmitters to obtain lossless RF-photonic links at a low transmitter power.

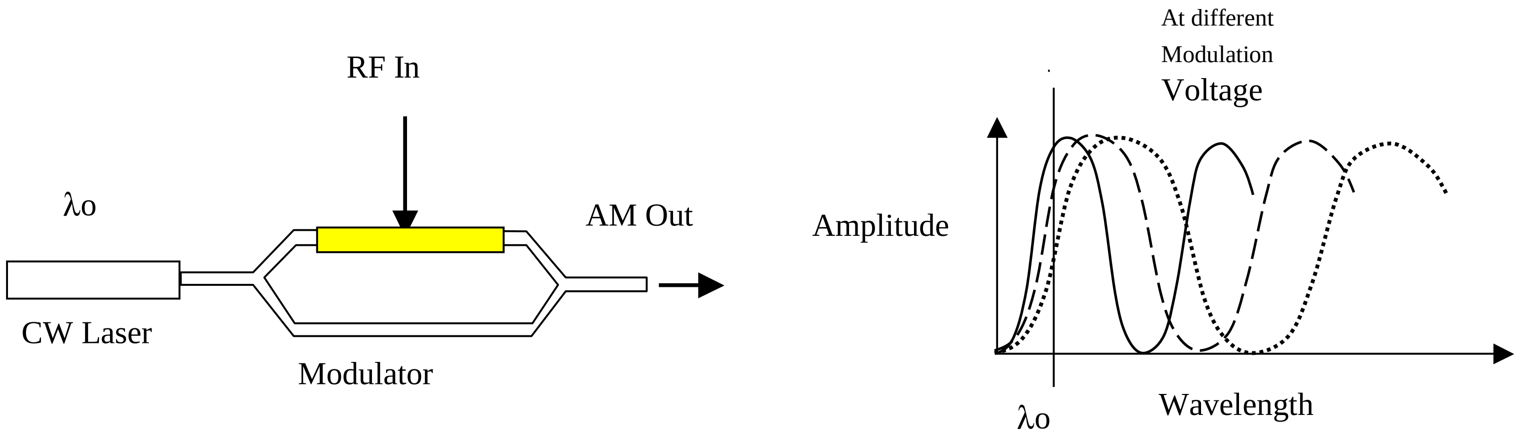
APPROACHES:

STARTING DATE: July 1, 2000. DURATION: 4 years.
1. Utilize the "FM-Gain" of an InP based integrated transmitter to overcome the RF-lightwave conversion and transmission loss. 2. Use the "Photonic Crystal" concept to build a slow-wave optical waveguides in $LiNbO_3$ and achieve low-V_π modulators.

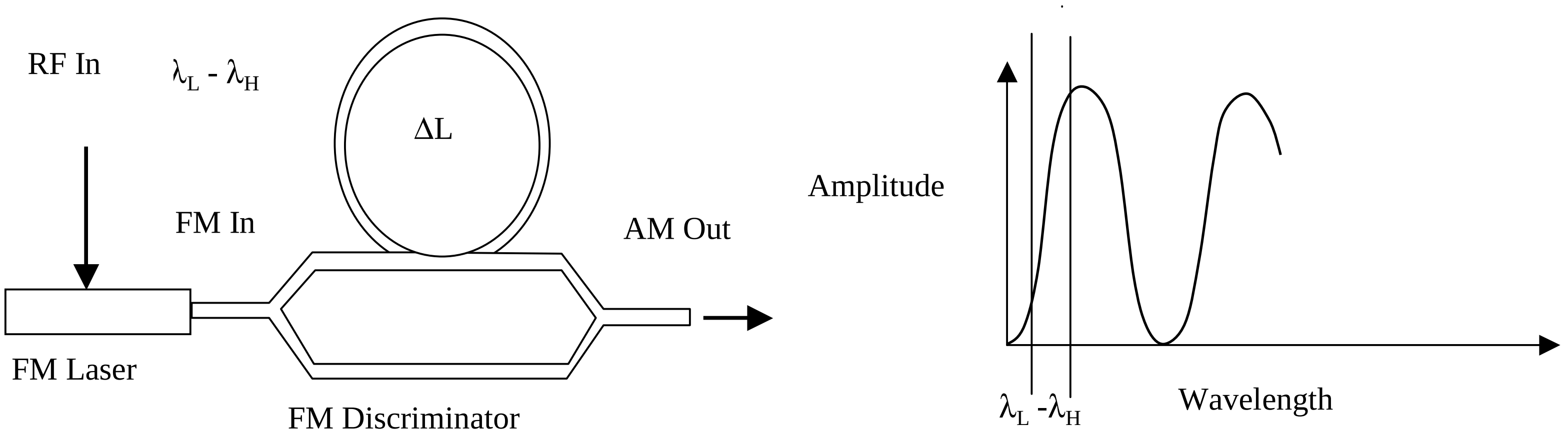
MILESTONES:

1. Design and fabricate high-FM-efficiency semiconductor lasers, FM discriminators, and achieve their integration as well as system testings.
2. Design and fabricate slow-wave optical waveguides based on the principle of "photonic bandgap". Obtain low-V_π $LiNbO_3$ modulators.

Review Principles I



Intensity Modulation

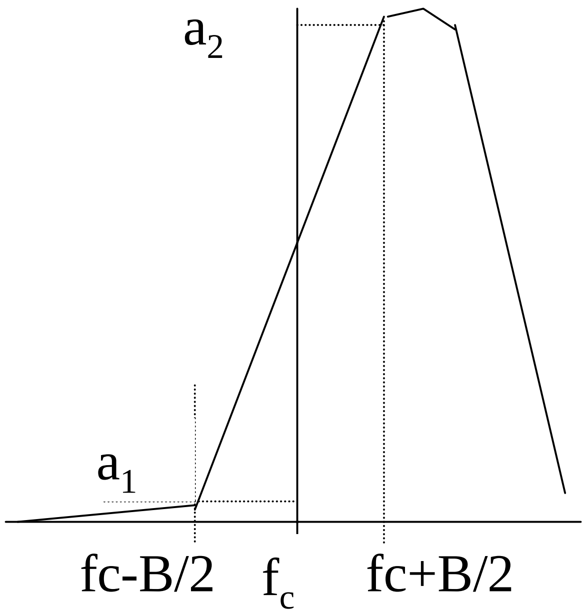


FM-based Intensity Modulation

Link Gain

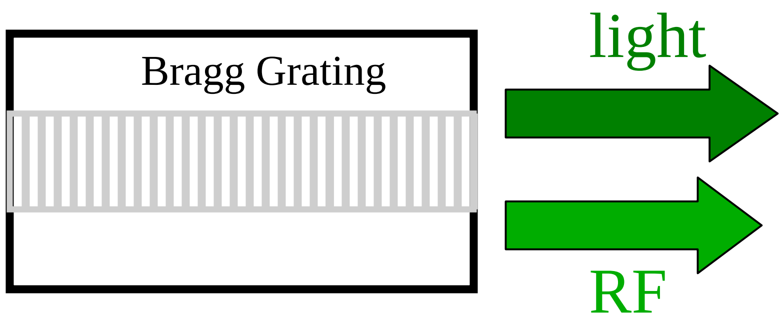
The RF Gain, G= ($RPLK(a_2-a_1)/B)^2$

Where,
R is the responsivity of the photodiode,
P is the transmitter power,
L is the insertion loss,
K is the FM efficiency (Hz/A) of the FM laser,
B is the usable bandwidth of the optical filter, $B \geq 2(\beta+1)f_m$
a_2 and a_1 are transfer coefficient at $fc+B/2$ and $fc-B/2$

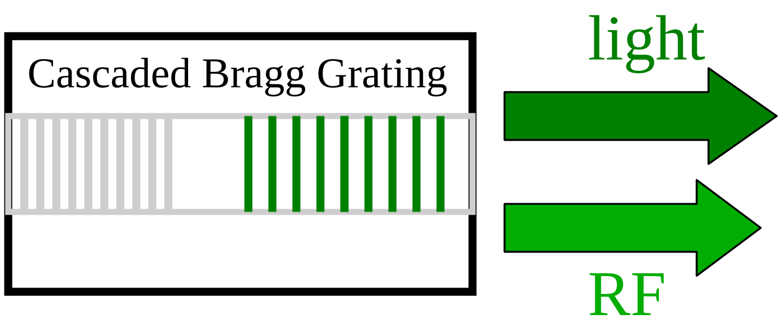


Optical filter transfer function

Review Principles II

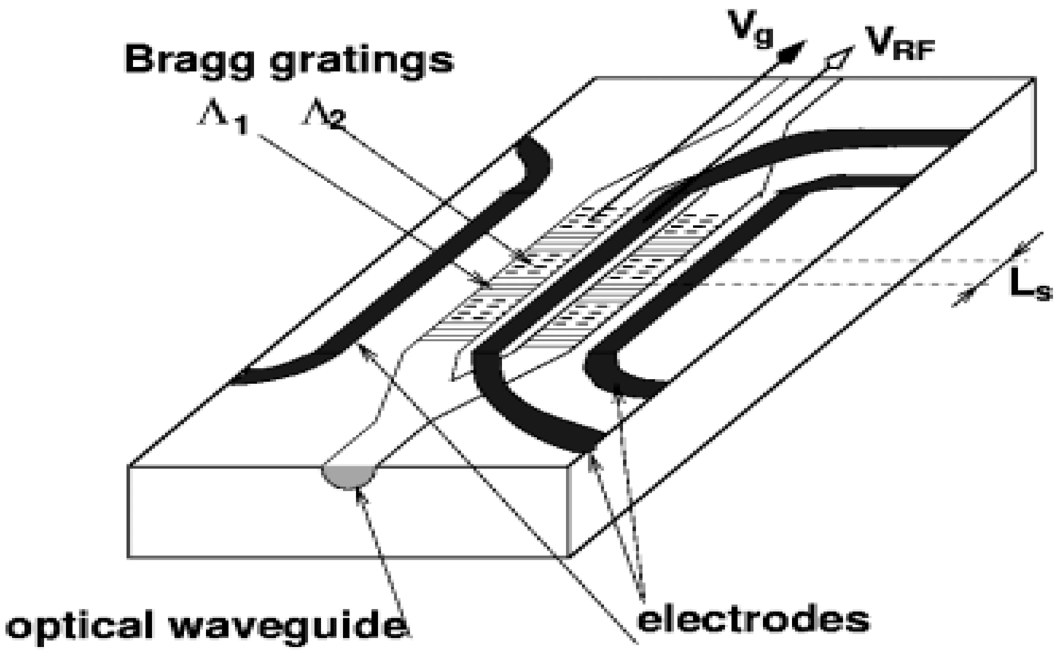


The group velocity dispersion is too high - use cascaded Bragg gratings.



- We propose to slow down the optical wave instead of accelerating the RF wave using Bragg grating
- Advantages:
  - no need for spacer or thick electrodes = larger overlap between RF and light waves
  - longer interaction time = larger effective length
  - easy to design 50Ω impedance.

Proposed Design



- Design wavelength: 1.55 μm
- Bragg grating periods are .35 and 0.36 μm
- Segment length 1mm
- Total length 2cm
- Number of segments 20

Issues Need to be Addressed

1. How to do grating fab. on $LiNbO_3$ crystals.
2. Is the two-tone spur-free dynamic range measurement representing a true evaluation of the linearity of an FM based system? (will be detailed at the discuss section)
3. How does an FM laser work? How the frequency change was accomplished?
4. What is the speed limit of the FM modulation scheme?
5. How to achieve the maximum FM efficiency?
6. How to the linearize the FM laser and the frequency demodulator?

TECHNICAL ACCOMPLISHMENTS LAST YEAR

1. Low V_{π} modulators:

• Theoretical studies of reduced-GV optical waveguides and effects of the cascaded gratings.

• Numerical modeling for mode matching and loss minimization.

• Developing methods to fabricate cascaded gratings on LiNbO3 waveguides.

• Initial sample fabrications.

2. FM laser/demodulator links:

- Understand the relationship between the two-tone SPDR measurement and the linearity of a FM system. Make sure our FM-gain approach are sound and correct.
- Verify our system results: "More than 10dB RF link gain at an optical power of smaller than 0 dBm and with SPDR of 120 dB-Hz $^{2/3}$" using different DFB/Mod FM laser devices.
- Study and understand the frequency modulation process and limits of the FM laser.
- Design the high FM efficiency lasers.
- Design the integrated FM laser/Demodulator devices.
- Start device fabrications

The Most Significant Accomplishment

1. Grating Fabrication on $LiNbO_3$ waveguide devices.

2. Build up solid understanding on the FM system.

Key Milestones

Deliverables	Y1	Y2	Y3	Y4
Design and fabrication of high efficiency FM lasers	x	x		
Integration of FM lasers and demodulator		x	x	
System testing of integrated transmitters			x	x
Design of photonic-gap EOM structures	x			
Measurements of group velocity in photonic gap structures		x		
Fabrication and testing of lithium niobate photonic gap electrooptic modulators		x	x	
Integration of modulators with other components				x

Ultra-wide-band, low voltage electro-optic modulator with photonic-bandgap structure

(Project 1)

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Program Objective

To develop integrated Electro-Optic $LiNbO_3$ modulator which exhibits:

- *Low V_p (Highly Efficient)*
- *Broad Instantaneous Bandwidth*
- *Low Insertion Loss*

Based on Group-Velocity Decreased $LiNbO_3$ Waveguides.

This Project Addresses the DoD's Needs for

- *efficient optical RF links and subsystems*
- *RF signal detection, remoting, and processing*

Background

EO-Modulator is one of the key components in RF-Photonics

$LiNbO_3$ modulatord with 10 mW receiving power:

V_π~ 5 Volts: ~ Link loss 22 dB

V_π~ 0.5 Volts: Link loss 5 dB

High Bandwidth > 20 GHz

JDS Uniphase: DC-18 GHz, V_π > 8 Volts

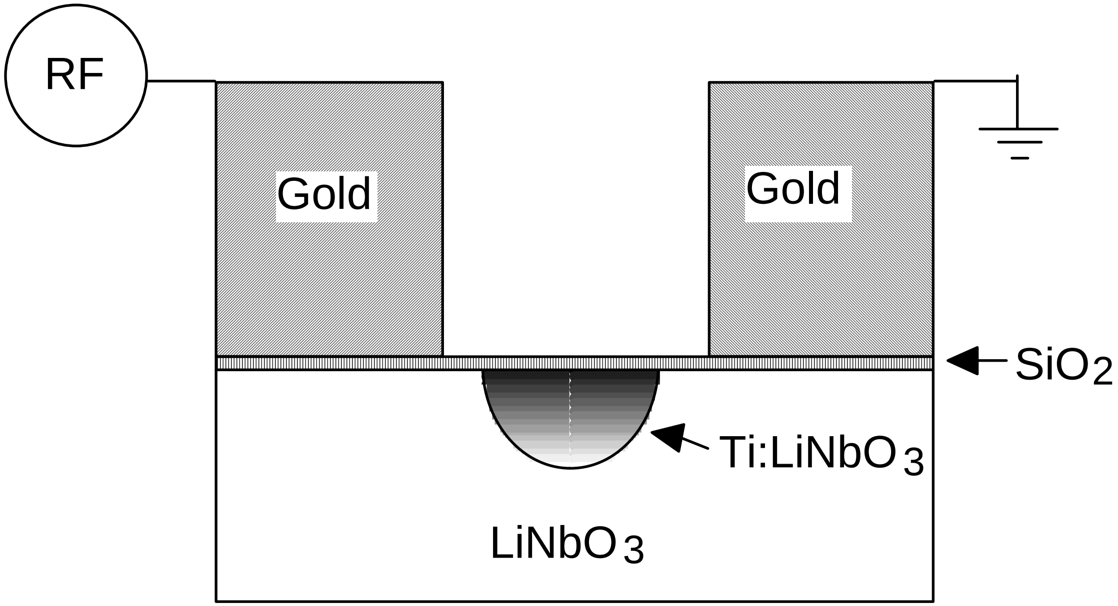
Lucent Tech: DC~30 GHz, V_π > 8 Volts

SDL: DC-18 GHz, V_π > 8 Volts

NTT: DC-35 GHz, V_π > 8 Volts

Background

Conventional Broadband E-O Modulators Manipulate V_g of RF signal to velocity match --> increased V_π



$v_{g,RF}$ ~ 4.2 for thin electrodes

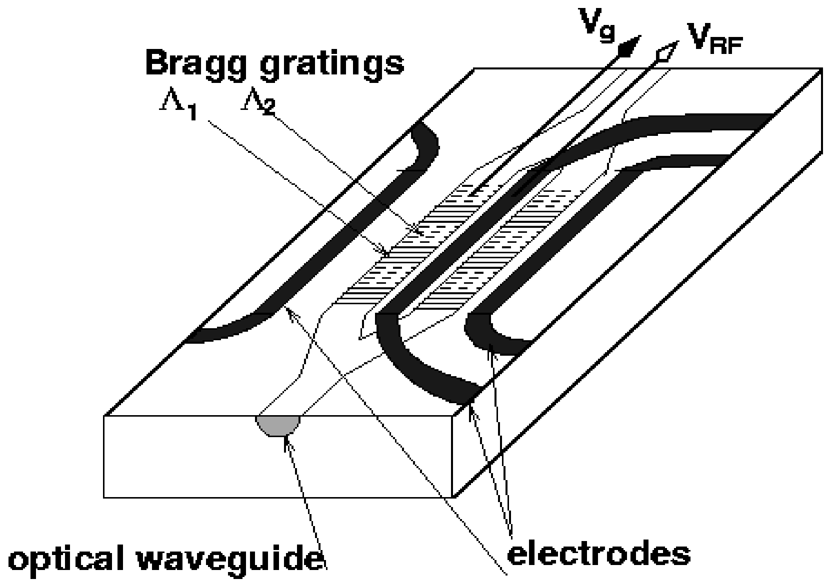
for thicker electrodes v_{gRF} ,

v_g ~ 2 for 1550 nm light

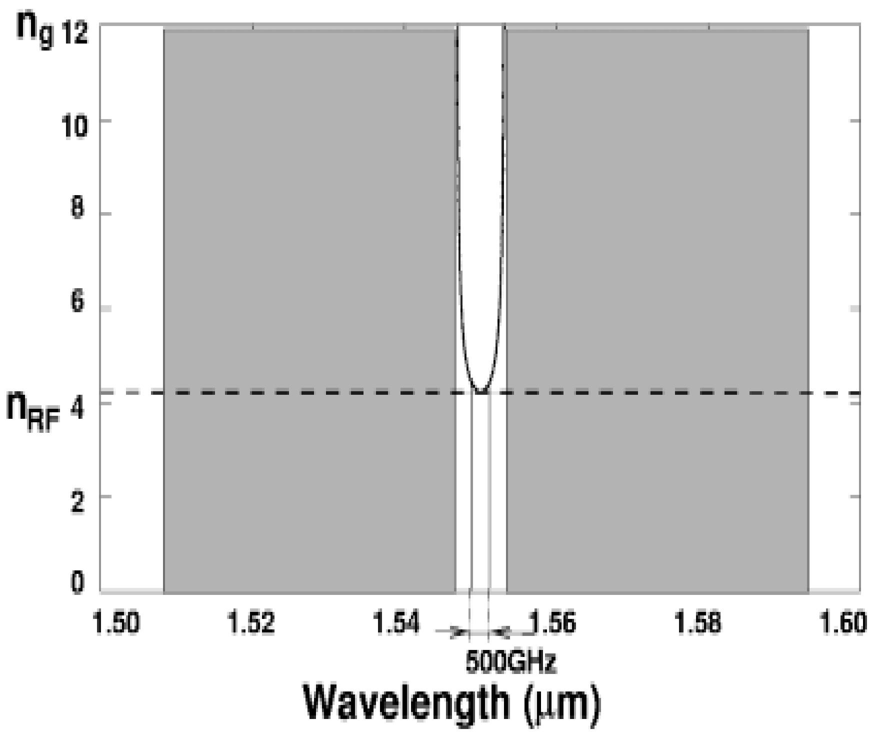
Background

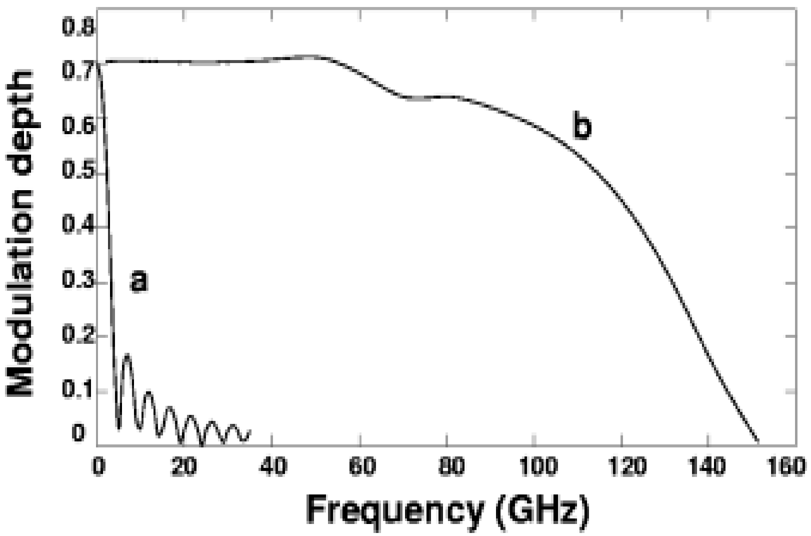
Reduced Group Velocity Ti:$LiNbO_3$ Optical Waveguides

- *Uses well understood and established Bragg Grating Technology*
- *Easy control of optical wavelength and RF/optical bandwidth*
- *Allow use of thin electrodes*
- *Increased effective interaction length*



Background





a: without gratings
b: with gratings

Bandwidth > 100 GHz
$V_\pi \sim 1$ volt

Design Issues

Optical Waveguides:

- Optical Mode Matching to Fibers
- Losses

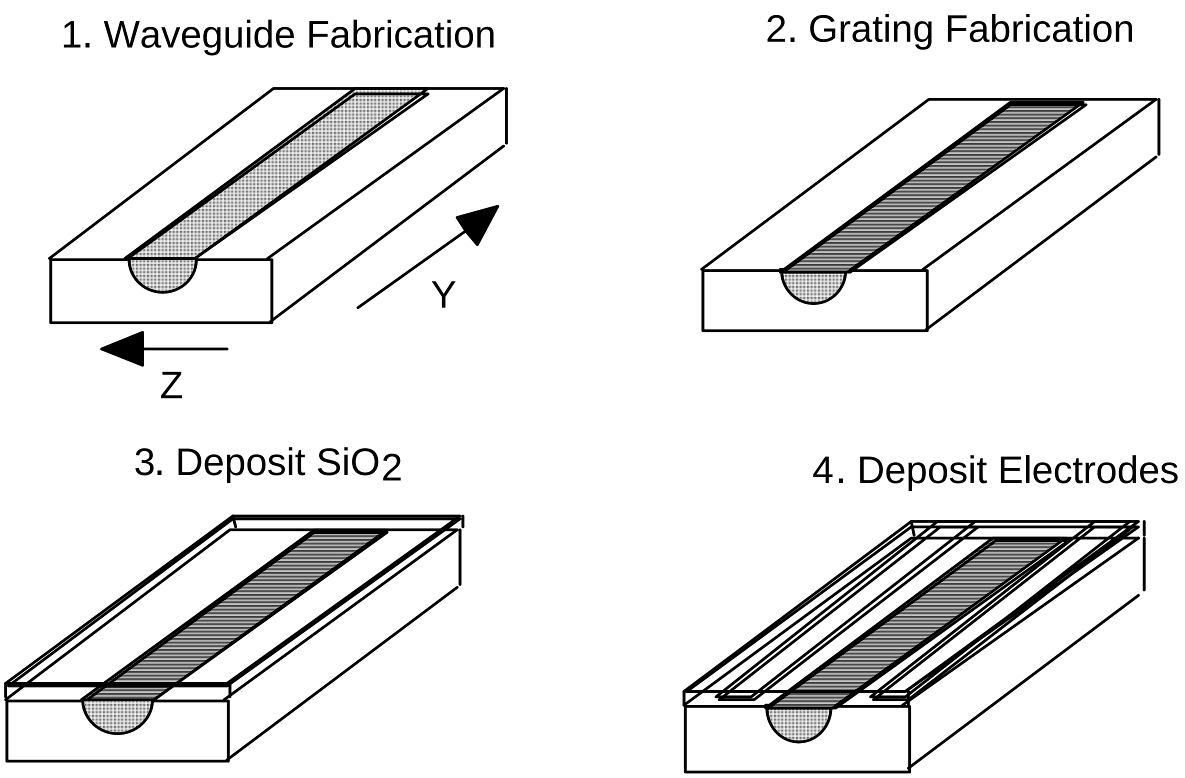
Gratings:

- Fabrication Issues
- Useful Spectral Window
- Losses

Electrodes:

- Impedance Matching, 50 Ω
- RF Losses
- Field Overlap

Envisioned Fabrication Steps

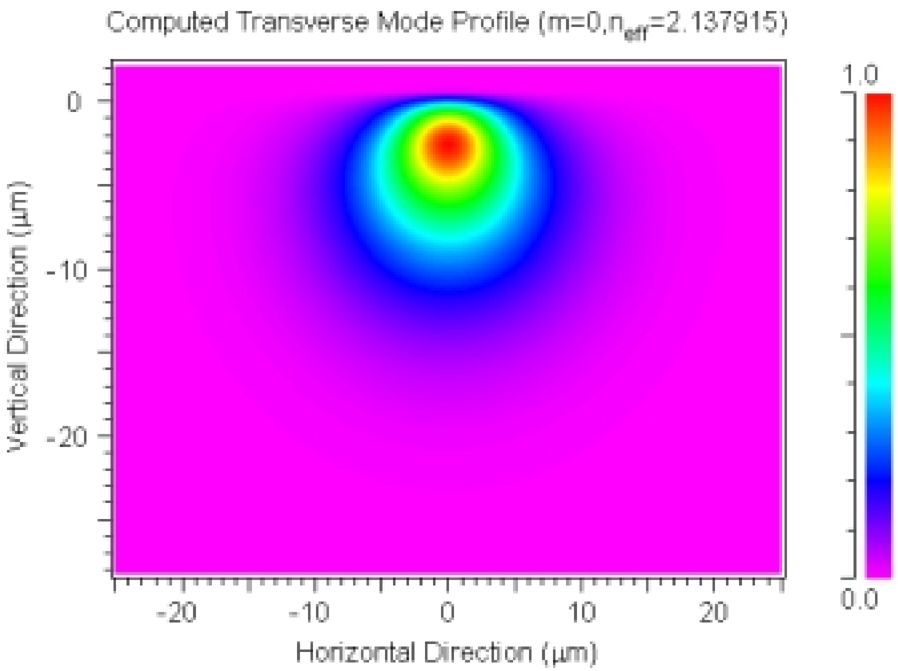


- Uses r_{33}
- Initially use holographic gratings
- Ion Milling to etch gratings
- Use Gold or Copper as Electrodes

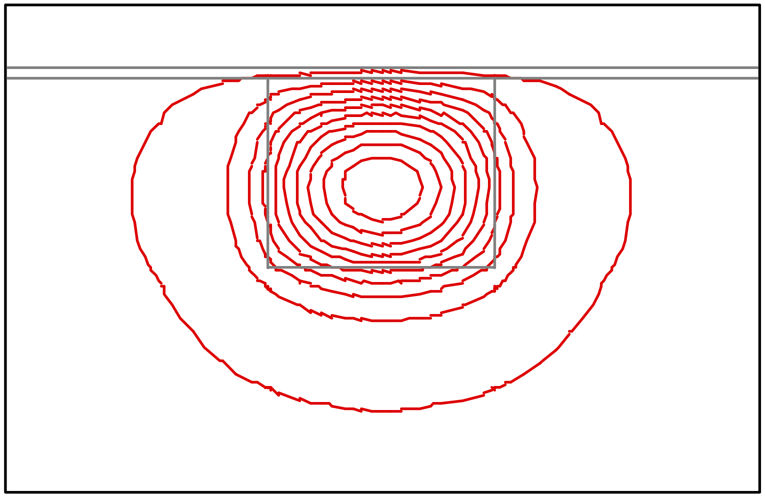
Optical Waveguides Optimization

- Use of In-house developed and commercial software to optimize optical waveguide structure.
- Preliminary results for Temp=1050, time=10 hr

As function of diffusion time, temperature and Ti



SiO_2 Thickness > 250 μm



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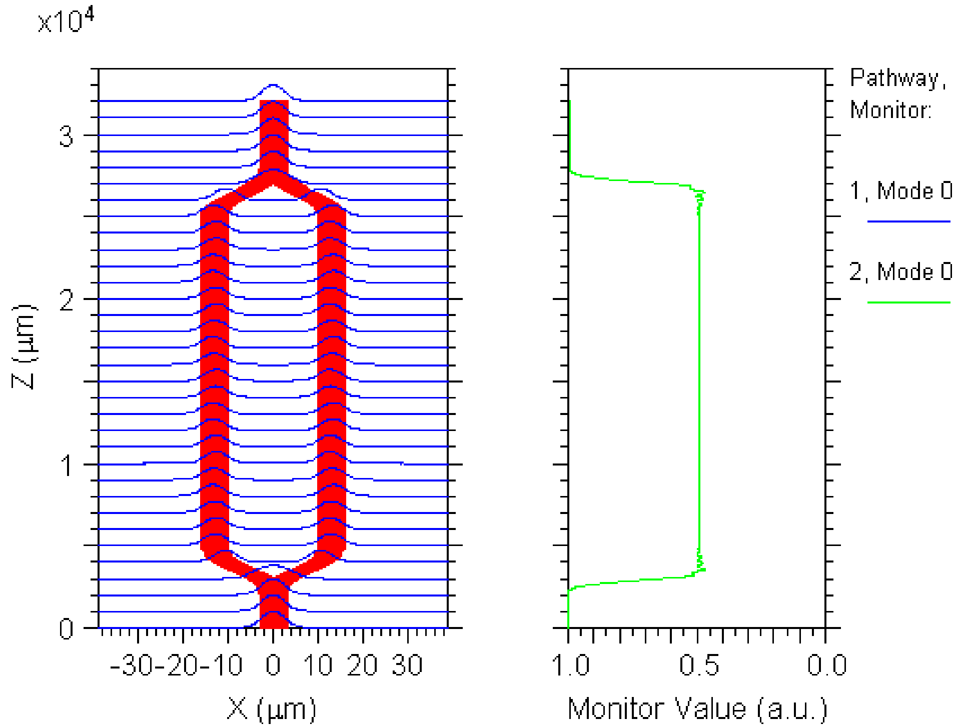
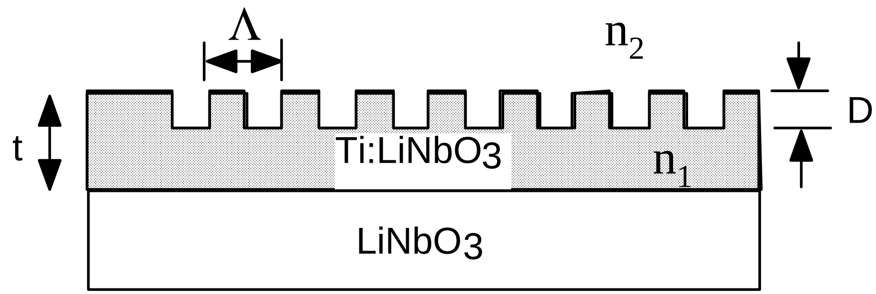
Optical Waveguides Optimization

Bend Loss, Y-junctions (splitter, combiner)

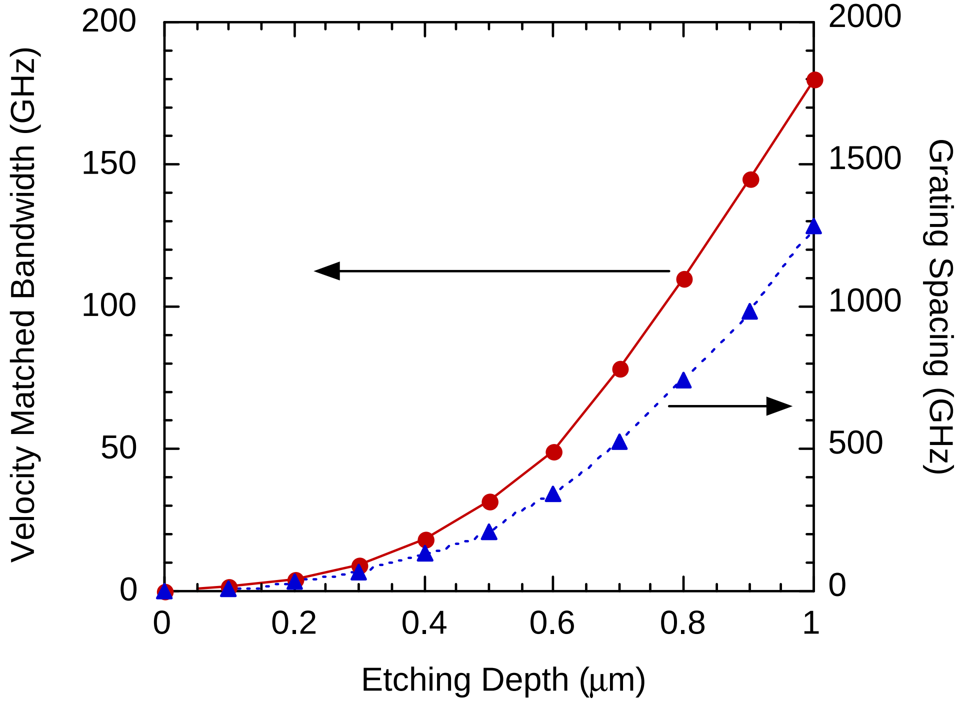
13 μm over 3 mm, 0.25 deg,
26 μm separation minimize coupling between two waveguides



Grating Structure



Cascaded Gratings to achieve n_g ~4.2



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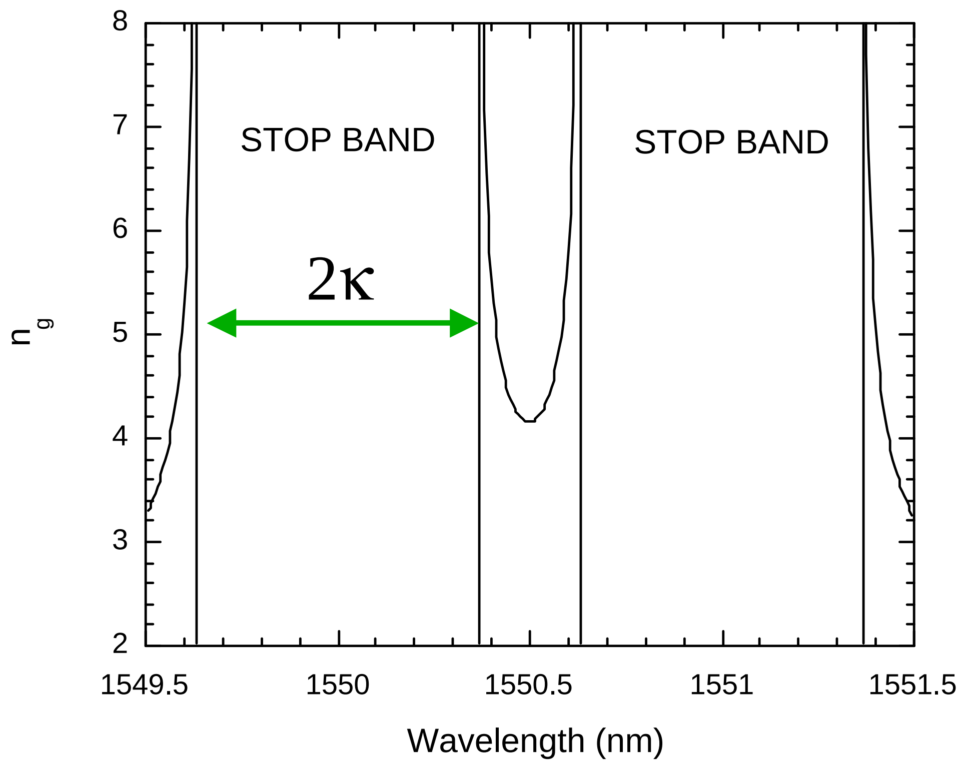
Grating Structure

Group Velocity Dispersion for D=0.4 microns

$$\kappa = \frac{-\omega\varepsilon_0}{4\pi L}\int_{-\infty}^{\infty}\Delta n^2(x)\left[\zeta_y(x)\right]^2 dx$$

$$\Delta n^2(x) = n_1^2 - n_2^2 \quad \text{for} \quad -D \le x \le 0$$



$$(\beta - \beta_B)^2 = \left(\frac{n}{c}(\omega - \omega_B)\right)^2 - \kappa^2$$

$$n_g = n_{eff} + \omega\frac{\partial n_{eff}}{\partial \omega}$$

Sample Fabrication

- Z-cut $LiNbO_3$ Wafers- Supertronics Corp.

- Ti-Diffused Waveguide Fabrication

  Width: 4-8 microns, Straight and MZ designs, ~5-6 microns deep

- Grating Fabrication

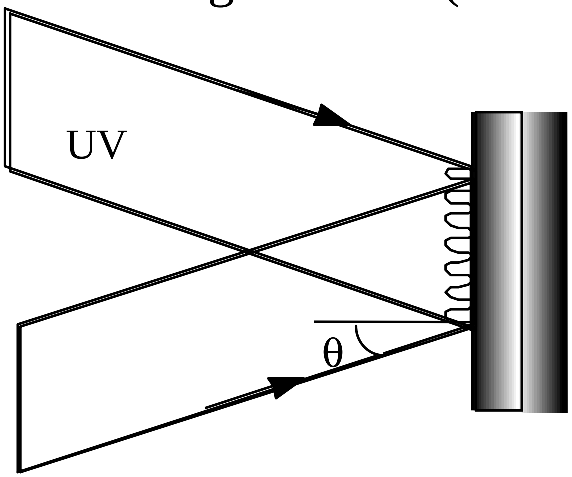
  Holographic grating using a standard lithographic technique

  Ion Milling for the grating etching

- Dicing and Polishing - JDS Uniphase

Designed grating period:

UV light source (441.6 nm) for the writing



$$\Lambda = \frac{\lambda_{UV}}{2\,Sin\left(\frac{\theta}{2}\right)}$$

$$\lambda_{Bragg} = 2\,n_{eff}\,\Lambda\;, \qquad n_{eff} \approx 2.2$$

		Incident Angle (θ)	λ_{Bragg} (μm)	$\Lambda_{grating}$ (μm)
Gratings	1	39.11	1.53802	**0.34955**
	2	38.6	1.55720	**0.35391**
	3	39.11	1.53802	**034955**
	4	38.8	1.55047	**0.35238**

Grating Fabrication

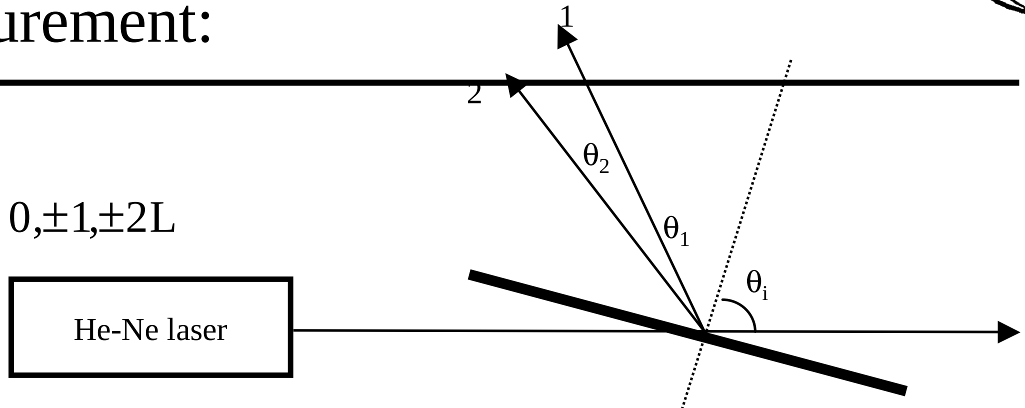
Shipley Microposit 1400-17 photoresist- 3500 RPM for 30 sec.
- ~200 nm thick photoresist

UV source- He-Cd laser, ~20 mW at 441.6 nm
generally 9 second exposure
1 minute developing

Freon 116 gas for ion milling, 115 min. ~ 250 nm deep grating

Grating Period Measurement:

$$\sin(\theta) = \sin(\theta_i) + q\frac{\lambda}{\Lambda}, \quad q = 0, \pm 1, \pm 2 \ldots$$



		$Sin(\theta_i)$	$Sin(\theta)$	$\lambda_{Bragg}(\mu m)$	$\Lambda_{grating}\ (\mu m)$
Sample A	1	-0.9362	0.86161	1.54871	0.35198
	2	-0.9362	0.87764	1.53525	0.34892
Sample B	1	-0.93204	0.85645	1.55685	0.35383
	2	-0.93204	0.87534	1.54057	0.35013
Sample C	1	-0.94157	0.87626	1.53168	0.34811
	2	-0.94157	0.86567	1.54066	0.35015
Sample D	1	-0.9375	0.8707	1.53991	0.34998
	2	-0.9375	0.86312	1.53670	0.34925

Next Phase

- Measure the amplitude transmission of the waveguides

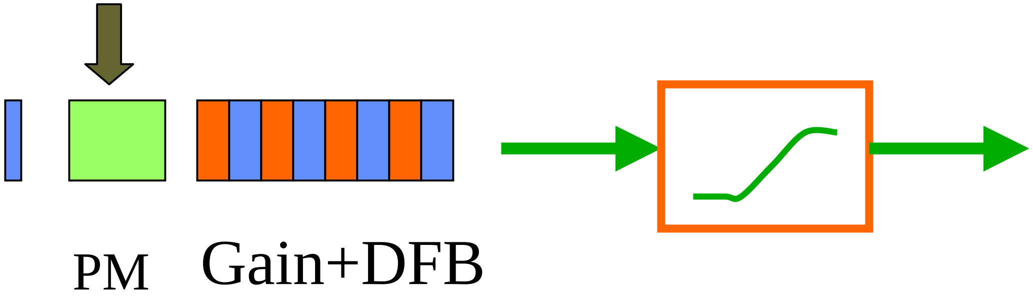
- Measure the group velocity of the waveguides

- Fabricate additional waveguides/grating

Studies on FM laser links

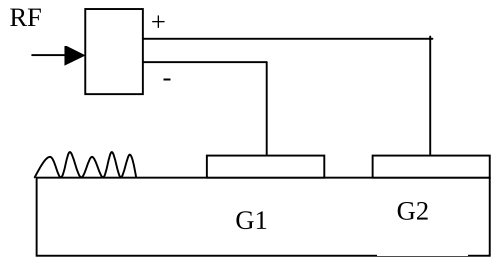
F-S Choa (UMBC), J. B. Khurgin, J. U. Kang (JHU)

Crucial issues in FM link

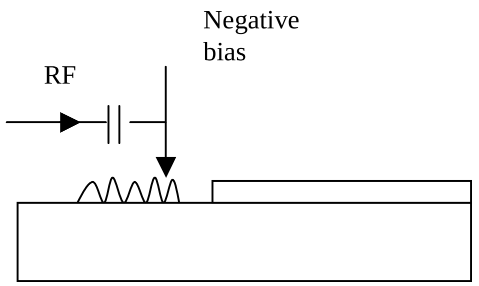


- High FM gain
- Linearity of the FM Laser
- Dynamic range
- Improving linearity of the FM demodulator.

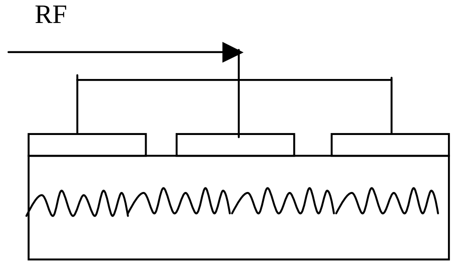
FM Lasers



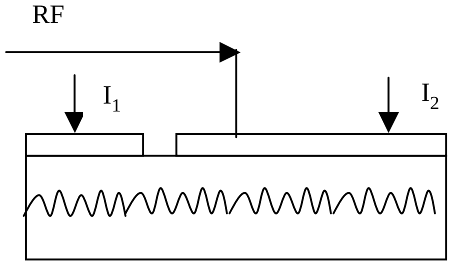
2-section DBR with push-pull modulation



Negatively baised DBR



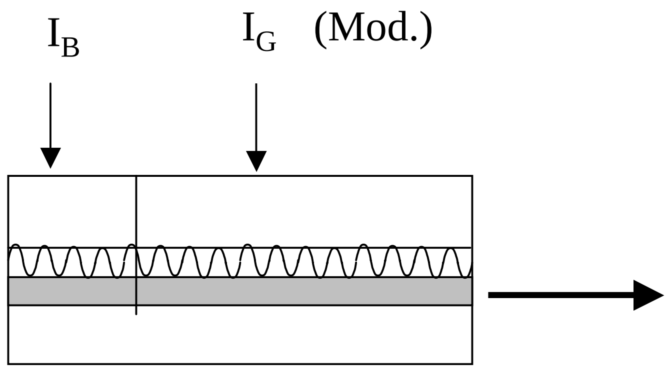
3-section DFB

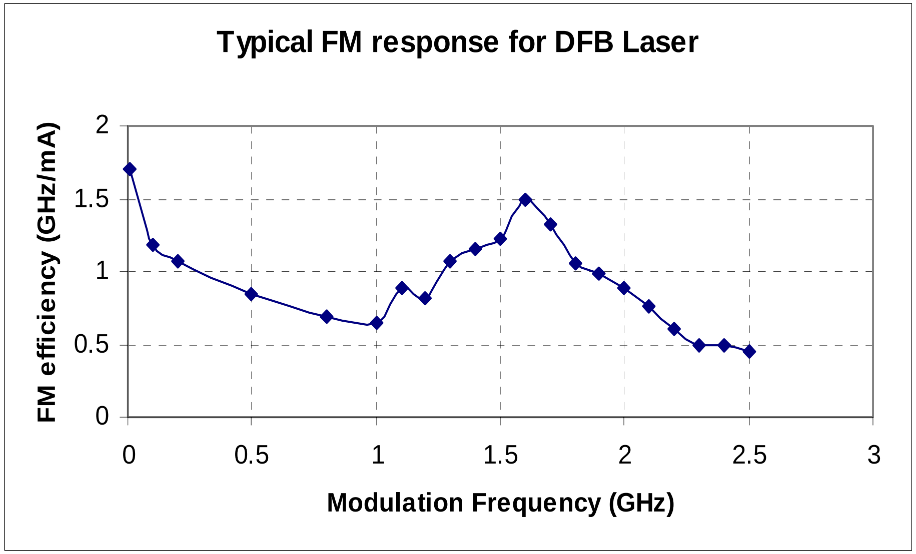


2-section DFB using Gain-lever effect

- All these structures can only achieve about 1GHz/mA FM efficiency in about 1GHz flat region

FM Lasers

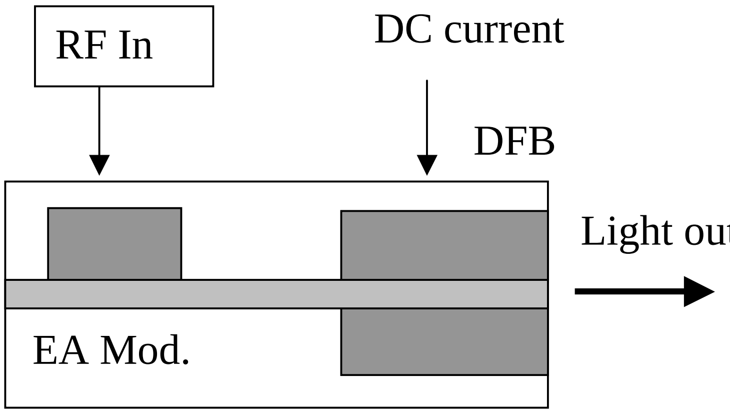


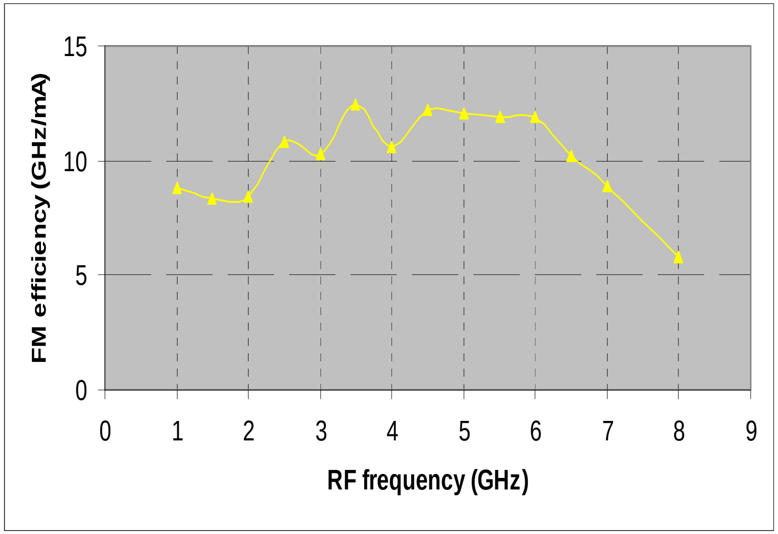


Using the gain levering effect – One section is heavily biased and becomes gain saturated -> Carrier injection can more effectively change the "index" than change the "gain".

The FM efficiency can be increased (still < 2 GHz/mA). However, the The FM BW is small and the response is not quite flat.

EA/DFB Based FM Lasers

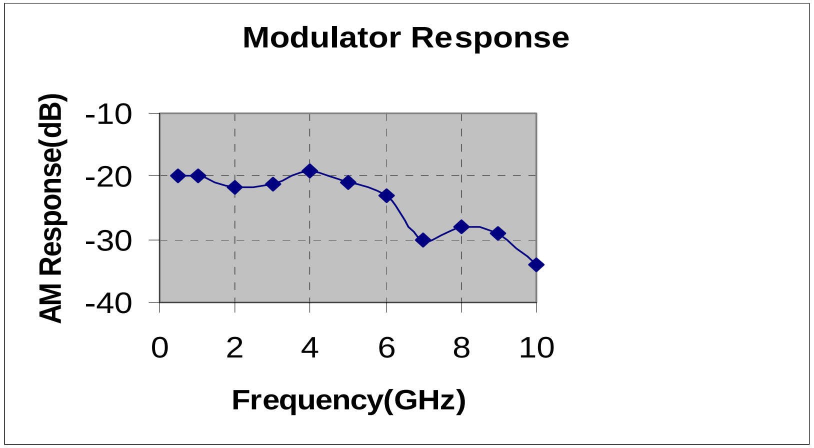




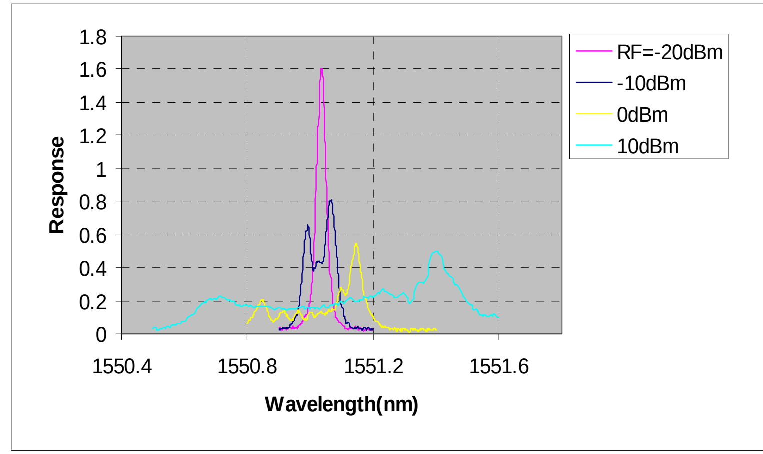
Better than Gain Levering effects:

1. No carrier clamping,
2. The QCSE can effectively change index with little gain modulation,
3. EA modulator speed can be much faster.

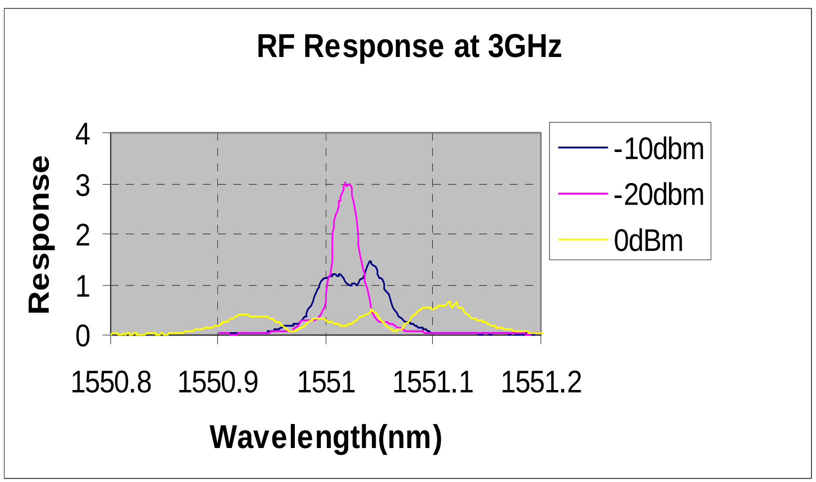
Modulation Characteristics



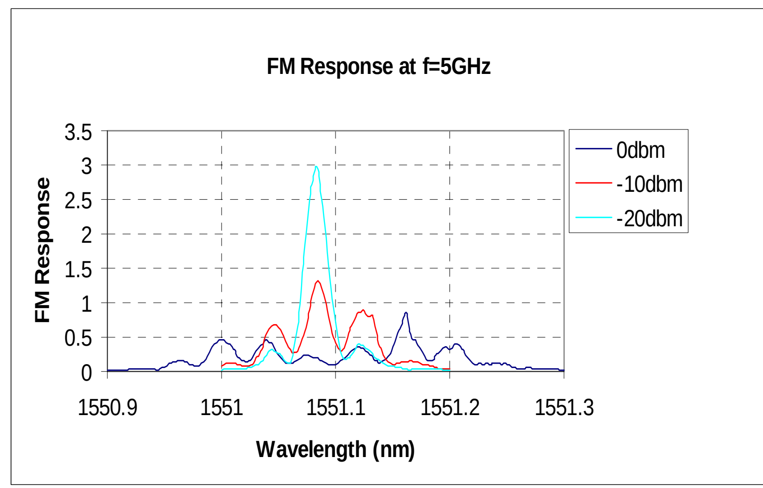
AM Modulator Speed



FM Spectrum at RF=2GHz



FM Spectrum at RF=3GHz

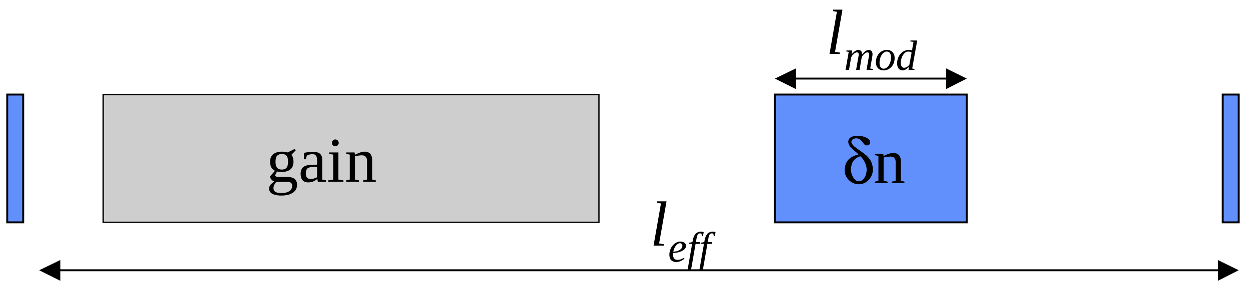


FM Spectrum at RF=5GHz

Highlights of modeling work:

- Coupled rate model of FM laser developed and tested
- Novel design of FM->AM converter proposed with better than 20dB improvement in dynamic range expected
- QCSE phase modulator modeled and its nonlinearity evaluated
- Length and bandgap of QCSE modulator optimized and tested

Understanding FM enhancement:



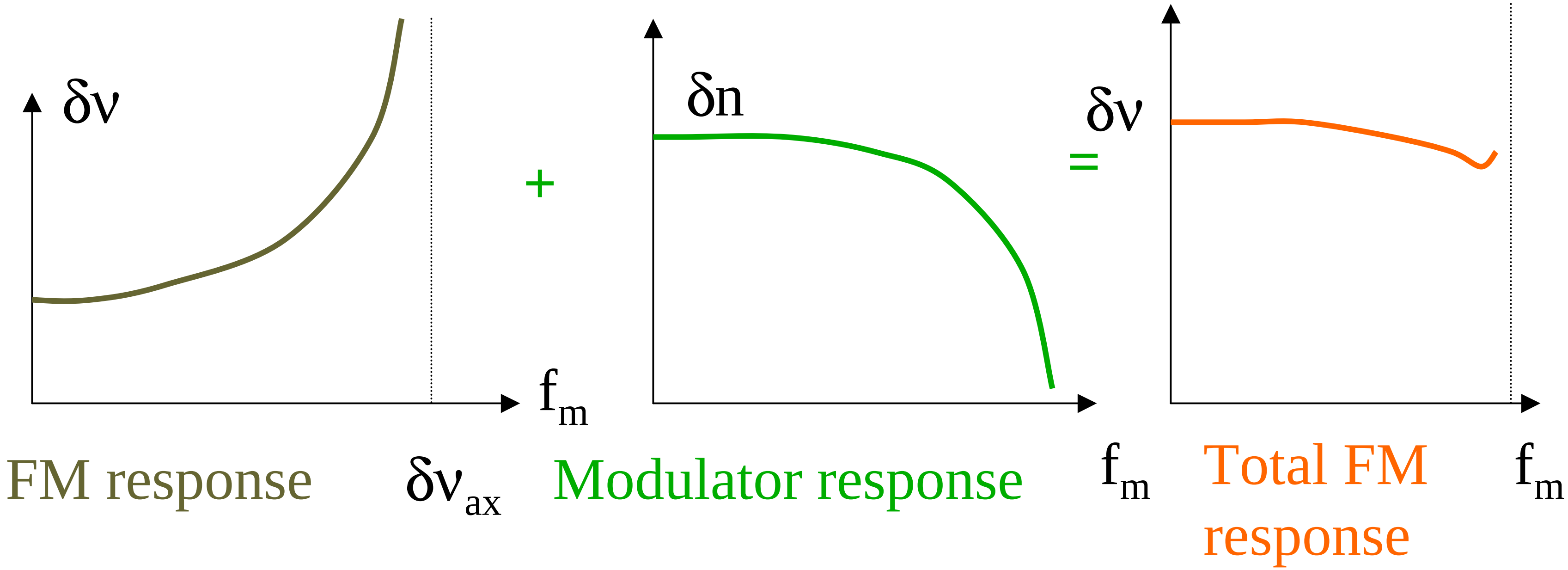
- Simple understanding: $$\frac{\delta\nu}{\nu} = \frac{\delta l_{eff}}{l_{eff}} = \frac{\delta n \times l_{\mathrm{mod}}}{l_{eff}} \approx K \times \delta n / n$$

- Main advantage: the frequency change is essentially instantaneous!(can be interpreted as instant Doppler shift by the “moving mirror”
- Resonant enhancement: when the frequency of FM -f_m approaches the difference between axial modes $\delta\nu_{ax}$ there is a resonance enhancement:

- but: coming too close to resonance may cause chaos/instability and then mode-locking - this is not what we want!

$$\frac{\delta\nu}{\nu} \approx K \frac{\delta n \cos(2\pi f_m t)}{n} \frac{f_m}{f_m - \delta\nu_{ax}}$$

How to take advantage of Enhancement?

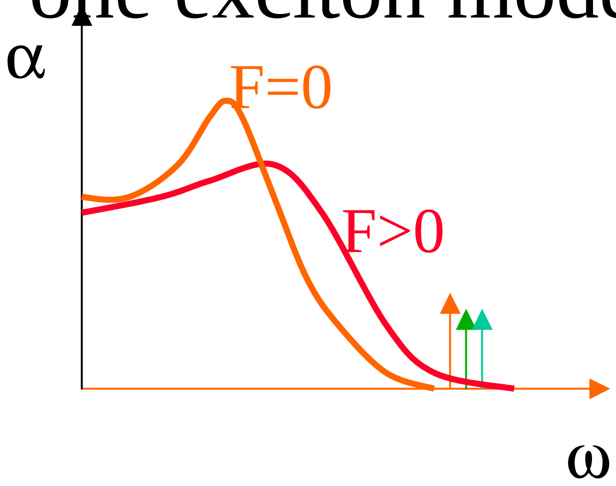


- By combining “roll up” FM response with “roll down” EA modulator response we expect to obtain flat FM response up to 20GHz.
- That requires long cavity length ~2mm - may create problems with the “fill factor” K.

Modeling the FM laser.

- Use the coupled mode approach.
  - Mode amplitudes: $\frac{\partial E_n}{\partial t} - [\frac{c}{2l_{eff}} G_n - \frac{1}{\tau_p}] E_n = \omega_n K \frac{\delta n}{n} [E_{n+1} \sin(\Phi_{n+1} - \Phi_n) + E_{n-1} \sin(\Phi_{n-1} - \Phi_n)];$
  - Mode phases: $\frac{\partial \Phi_n}{dt} + \left[\omega_n - \omega_q\right] = \omega_n K \frac{\delta n}{n} \frac{1}{E_n} [E_{n+1} \cos(\Phi_{n+1} - \Phi_n) + E_{n+1} \cos(\Phi_{n-1} - \Phi_n)]$
- Describe DFB section as a mirror with the gain G_n
- Describe the gain saturation as homogeneous: $G_n = \int \frac{G_{0,n}}{1 + \sum_{1}^{N} |E_m|^2 f^2(x) \Big/ P_{sat}} dx$

- Neglect spectral hole burning and FWM
- Describe the EAM modulator using simple one exciton model



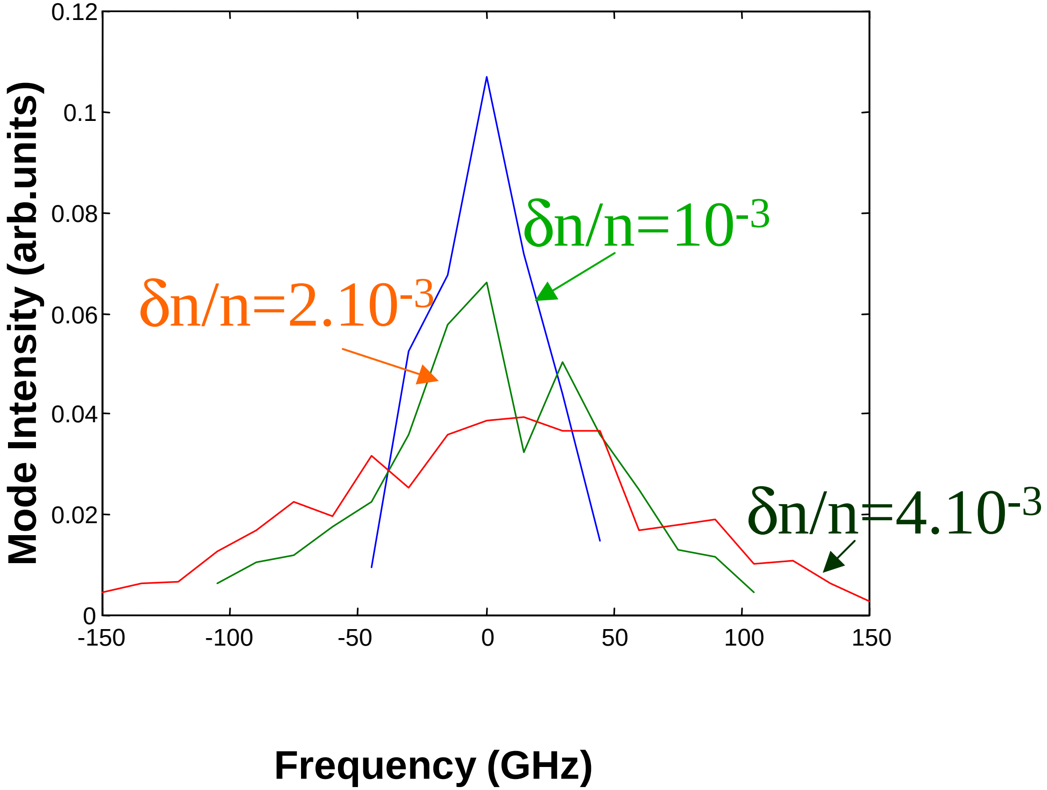
The expression for the index change is evaluated using Kramers-Kronig rule

$$\delta n_n = \frac{1}{\pi n} \int \frac{\alpha(\omega)}{\omega - \omega_n} d\omega$$

- The frequency response of EAM is RC

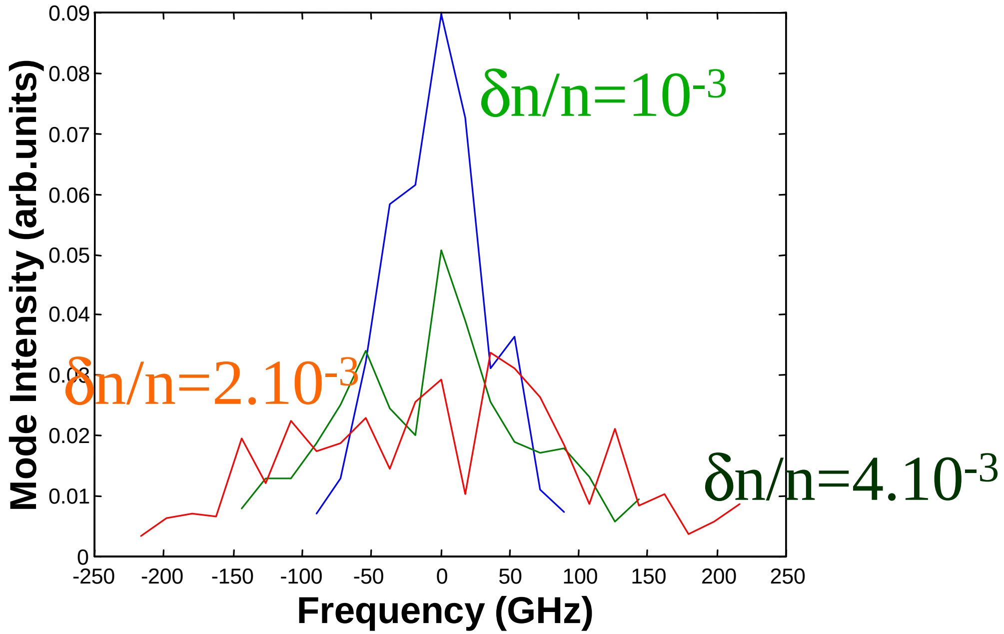
$$\delta n(f_m) = \frac{\delta n_0}{1 + 2\pi f_m RC}$$

Testing the model



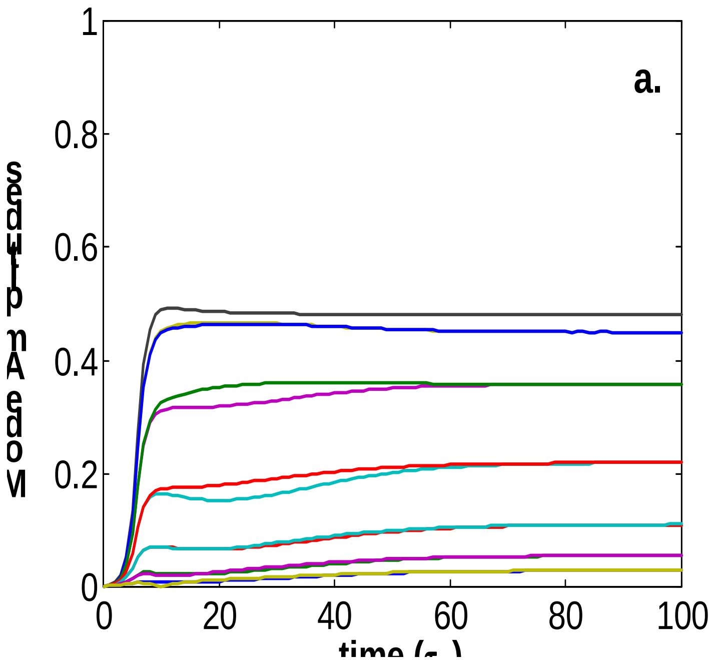
- Modulation frequency: 15GHz
- Mode distance: 20GHz

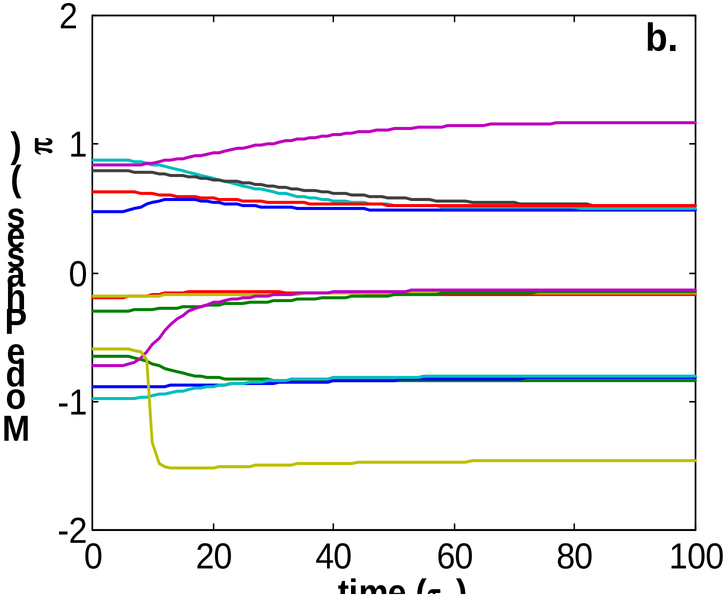
Testing the model (II)



- Modulation Frequency 18GHz
- Mode Distance 20GHz

Temporary evolution of mode phases and amplitudes.





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Success (qualified) of the model

- The model correctly predicts the spectrum of the signal as a function of amplitude of index modulation
- It shows the temporal response when the laser turns on
- It shows the evolution of phases of individual modes and predicts when the laser is going to become unstable - a very important achievement
- Since the model includes spontaneous emission (phenomenologically) we can obtain the phase noise - no other program is capable of it!

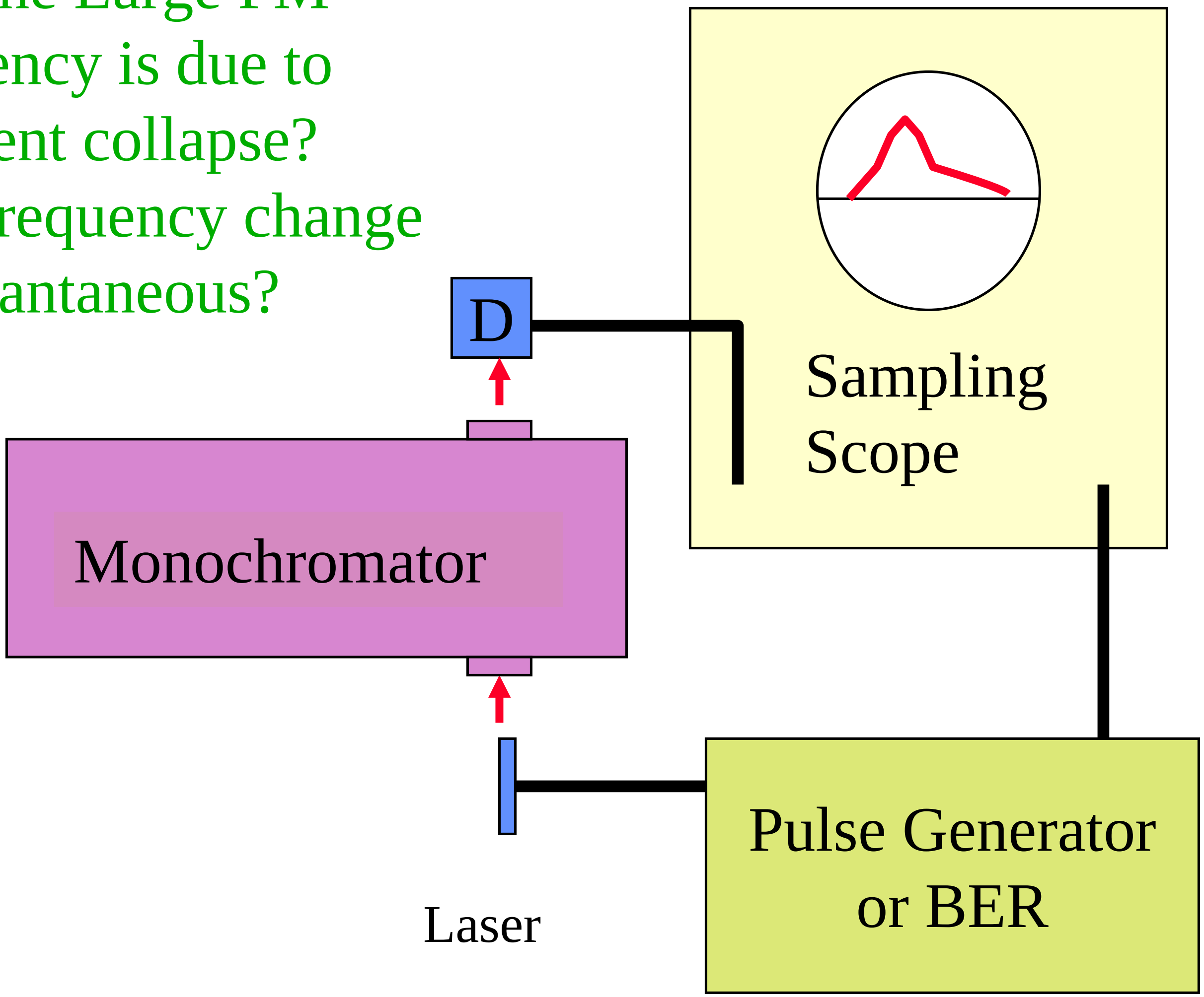
- BUT!

Shortcomings of the model:

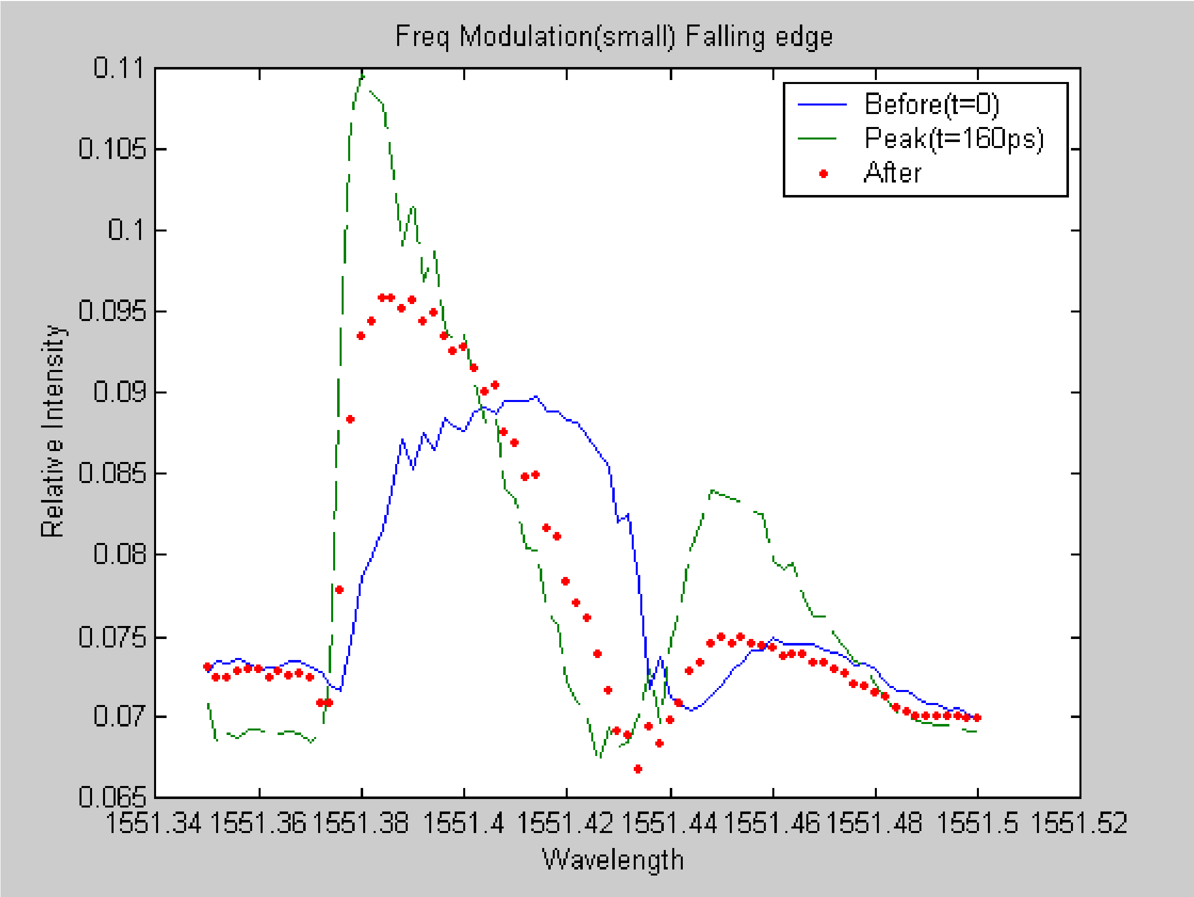
•Gain section in this model is a very crude model - not connected with actual semiconductor
•The gain saturation mechanism in reality is not purely homogeneous and it can play enormous role.
•We must find a reliable way to incorporate the material growth parameters into the model
•We need to develop a model for the phase modualtor

Measuring Time resolved spectra

Q1: The Large FM efficiency is due to coherent collapse?
Q2: Frequency change is instantaneous?

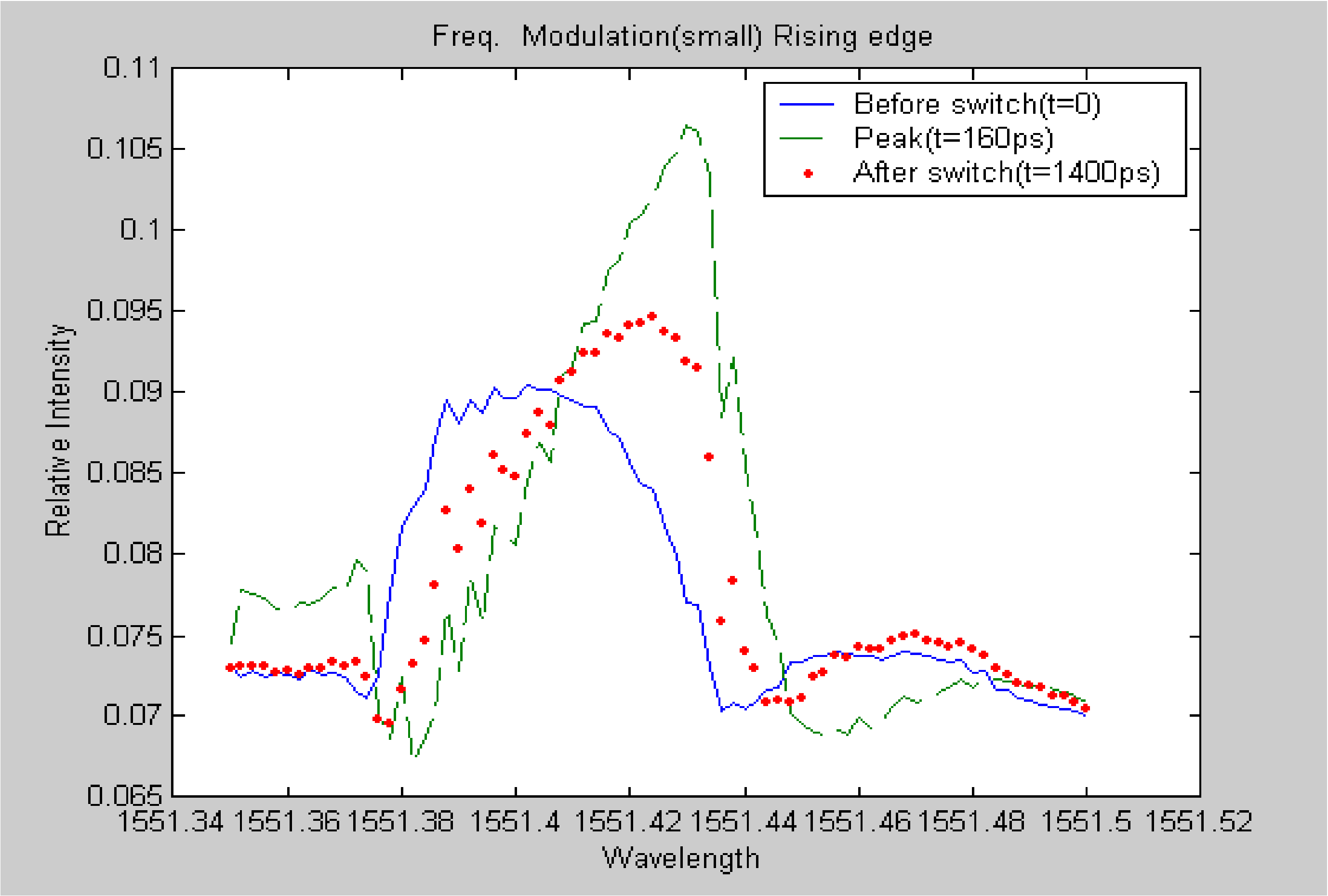


Time Resolved Spectra



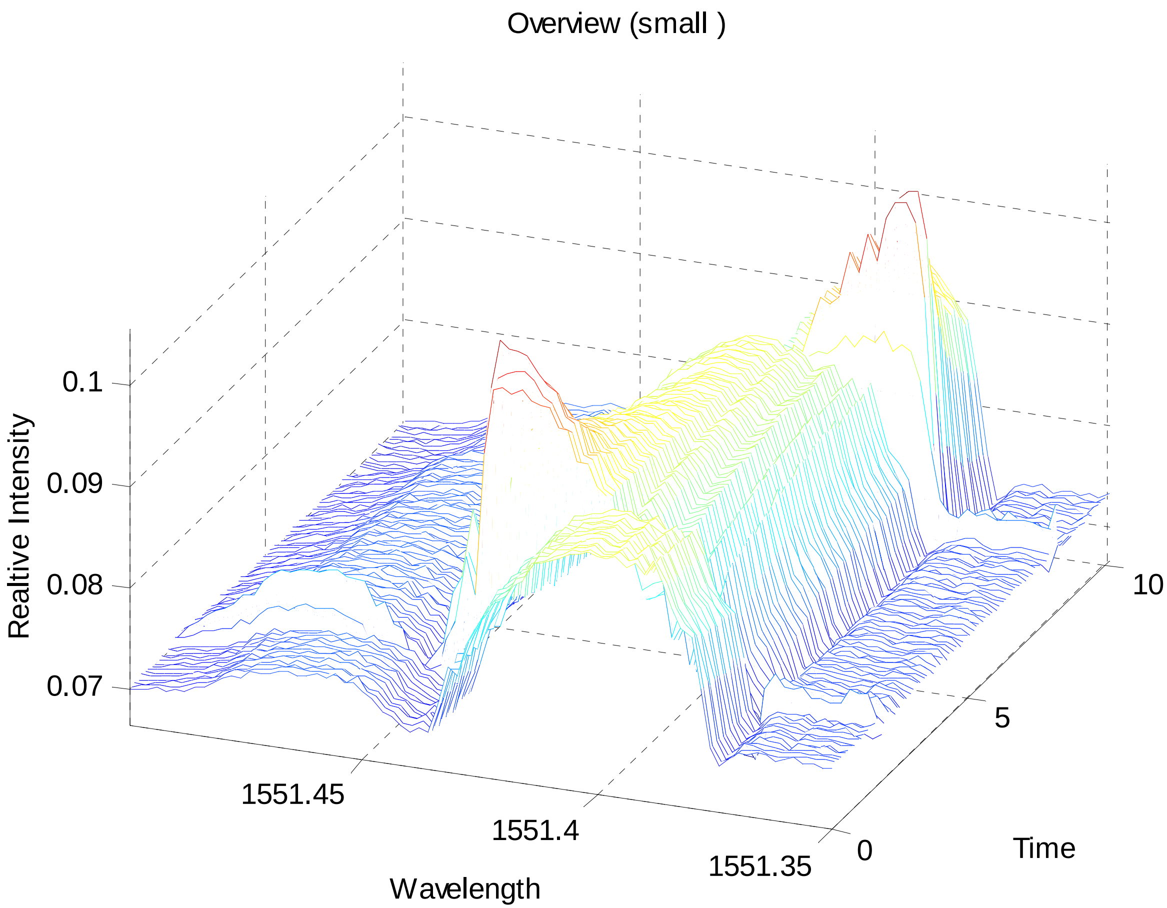
Under 5 Gb/s Digital Modulations

Time Resolved Spectra



Under 5 Gb/s Digital Modulations

Time Resolved Spectra

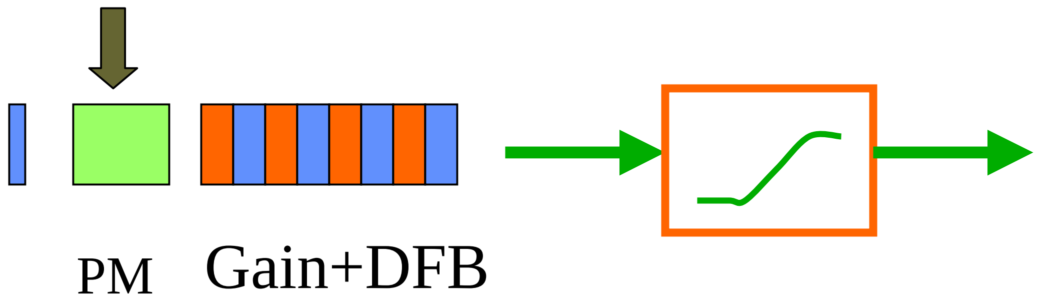


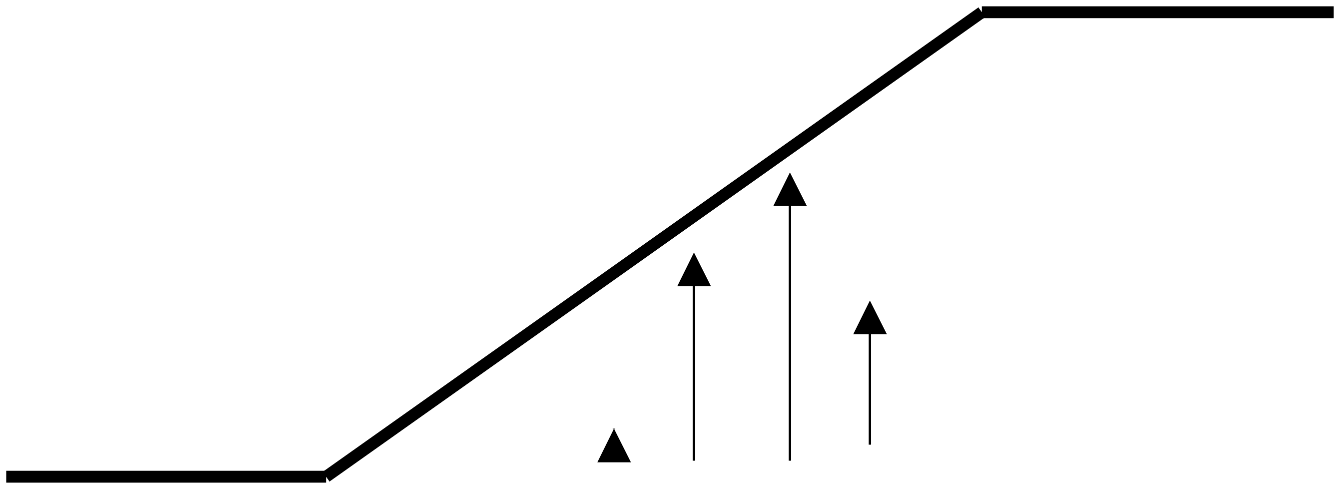
Under 5 Gb/s Digital Modulations

Study Conclusions

- The high FM efficiency is clean and real and is not from coherent collapse.
- The frequency change is caused by cavity mode environment change and the preferred lasing frequency drift from the old one to a new one. The old photons have to die and the new photons have to be built up. The process requires ~10 chip round-trip time to stabilize at the new frequency.
- The speed of the FM device may limit our proposed approach to operate at frequency smaller than 20 GHz because the round-trip time of an integrated DFB/MOD chip at a size of ~600 μm.
- The FM efficiency can be increased by enhancing the index change in the modulator or increase the modulator length.

Understand the FM system





Understanding Intermodulation of FM signal

$$m_i = \frac{\Delta f_i}{f_i}$$

$$E = E_0 \cos(2\pi f_0 t + \frac{\Delta f_1}{f_1}\sin 2\pi f_1 t + \frac{\Delta f_2}{f_2}\sin 2\pi f_2 t) =$$

$$E_0\left[\cos(2\pi f_0 t)\cos\left[\frac{\Delta f_1}{f_1}2\pi f_1 t\right]\cos\left[\frac{\Delta f_2}{f_2}2\pi f_1 t\right]\right] - E_0\left[\cos(2\pi f_0 t)\sin\left[\frac{\Delta f_1}{f_1}2\pi f_1 t\right]\sin\left[\frac{\Delta f_2}{f_2}2\pi f_1 t\right]\right] -$$

$$E_0\left[\sin(2\pi f_0 t)\sin\left[\frac{\Delta f_1}{f_1}2\pi f_1 t\right]\cos\left[\frac{\Delta f_2}{f_2}2\pi f_1 t\right]\right] - E_0\left[\sin(2\pi f_0 t)\cos\left[\frac{\Delta f_1}{f_1}2\pi f_1 t\right]\sin\left[\frac{\Delta f_2}{f_2}2\pi f_1 t\right]\right] =$$

$$E_0\left[\cos(2\pi f_0 t)\left[J_0(m_1) + 2\sum_k J_{2k}(m_1)\cos(4k\pi f_1 t)\right]\left[J_0(m_2) + 2\sum_l J_{2l}(m_2)\cos(4l\pi f_2 t)\right]\right] -$$

$$E_0\left[\cos(2\pi f_0 t)\left[2\sum_k J_{2k+1}(m_1)\sin((2k+1)2\pi f_1 t)\right]\left[2\sum_k J_{2l+1}(m_2)\sin((2l+1)2\pi f_2 t)\right]\right] -$$

$$E_0\left[\sin(2\pi f_0 t)\left[2\sum_k J_{2k+1}(m_1)\sin((2k+1)2\pi f_1 t)\right]\left[J_0(m_2) + 2\sum_l J_{2l}(m_2)\cos(4l\pi f_2 t)\right]\right] -$$

$$E_0\left[\sin(2\pi f_0 t)\left[2\sum_k J_{2k+1}(m_1)\sin((2k+1)2\pi f_1 t)\right]\left[2\sum_k J_{2l+1}(m_2)\sin((2l+1)2\pi f_2 t)\right]\right]$$

Terms with intermodulation ARE ALREADY here!!

Intermodulation (continued)

$$-E_0\left[\sin(2\pi f_0 t)\left[2\sum_k J_{2k+1}(m_1)\sin((2k+1)2\pi f_1 t)\right]\left[J_0(m_2)+2\sum_l J_{2l}(m_2)\cos(4l\pi f_2 t)\right]\right]=$$

$$-2E_0\sin(2\pi f_0 t)J_0(m_2)\sum_k J_{2k+1}(m_1)\sin((2k+1)2\pi f_1 t)$$

$$\boxed{-4E_0\sin(2\pi f_0 t)\sum_k J_{2k+1}(m_1)\sum_l J_{2l}(m_2)\sin((2k+1)2\pi f_1 t)\cos(4l\pi f_2 t)}$$

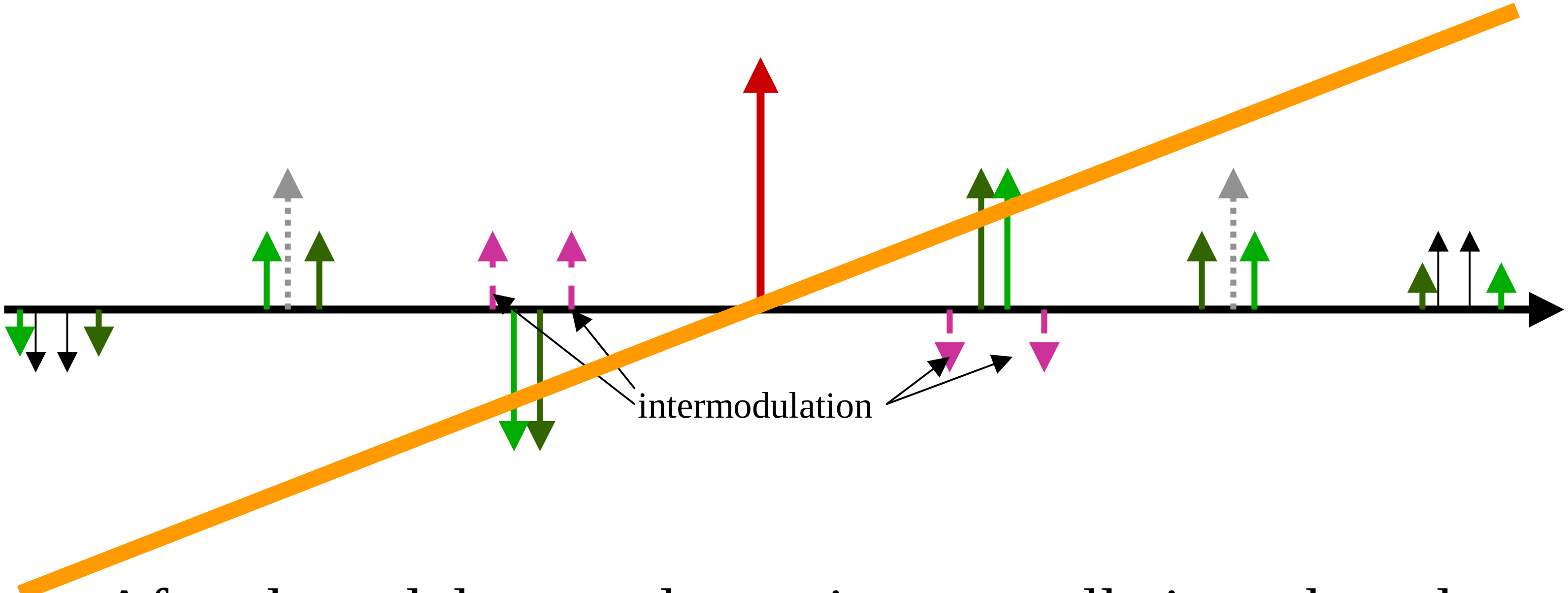
Lowest intermodulation term: *k=0;l=1*

$$-4E_0\sin(2\pi f_0 t)J_1(m_1)J_2(m_2)\sin(2\pi f_1 t)\cos(4l\pi f_2 t)=$$
$$-2E_0 J_1(m_1)J_2(m_2)\sin(2\pi f_0 t)[\sin 2\pi(f_1+2f_2)t-\sin 2\pi(2f_2-f_1)t]$$

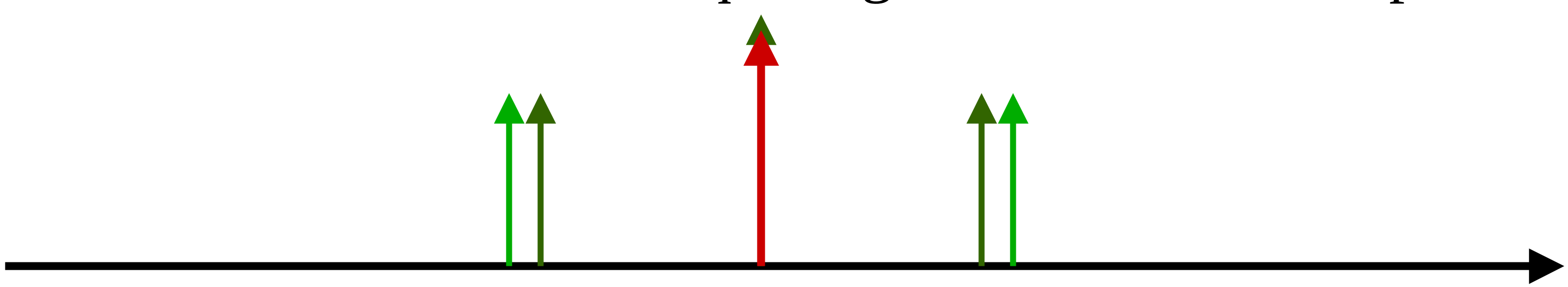
***Thus we have these terms*:**

$$E_0[J_1(m_1)J_2(m_2)\cos 2\pi(f_0-2f_2+f_1)t-J_1(m_1)J_2(m_2)\cos 2\pi(f_0+2f_2-f_1)t]+$$
$$E_0[J_1(m_2)J_2(m_1)\cos 2\pi(f_0-2f_1+f_2)t-J_1(m_2)J_2(m_1)\cos 2\pi(f_0+2f_1-f_2)t]$$

This is how the FM spectrum looks after the modulator/demodulator



After demodulator and squaring cancellation takes place:



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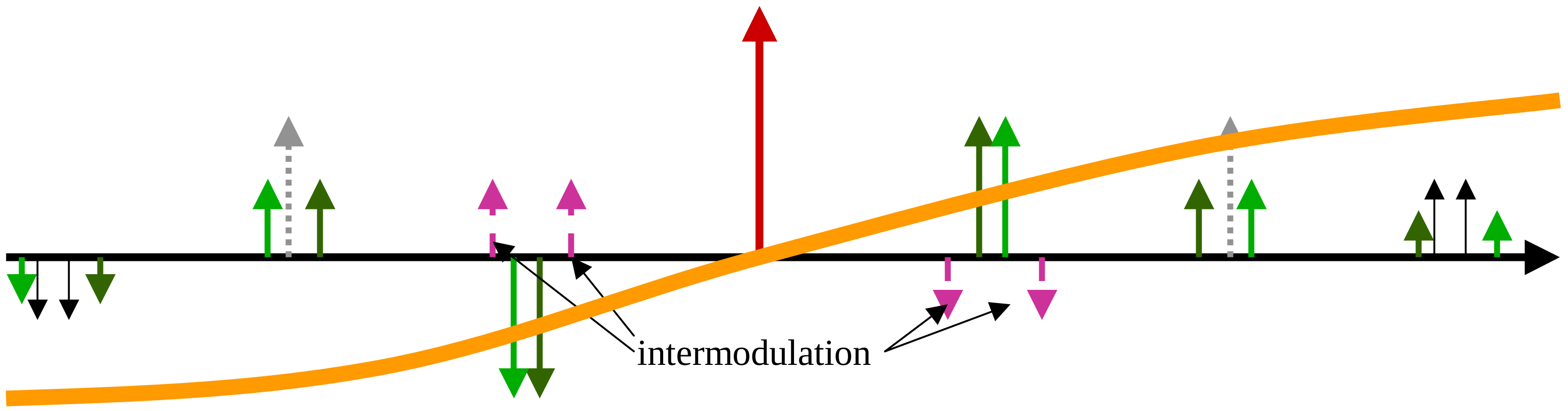
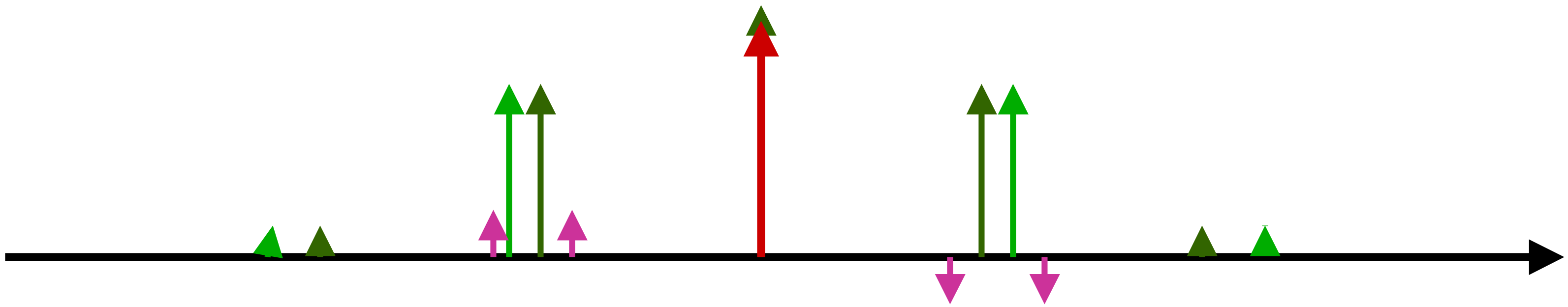


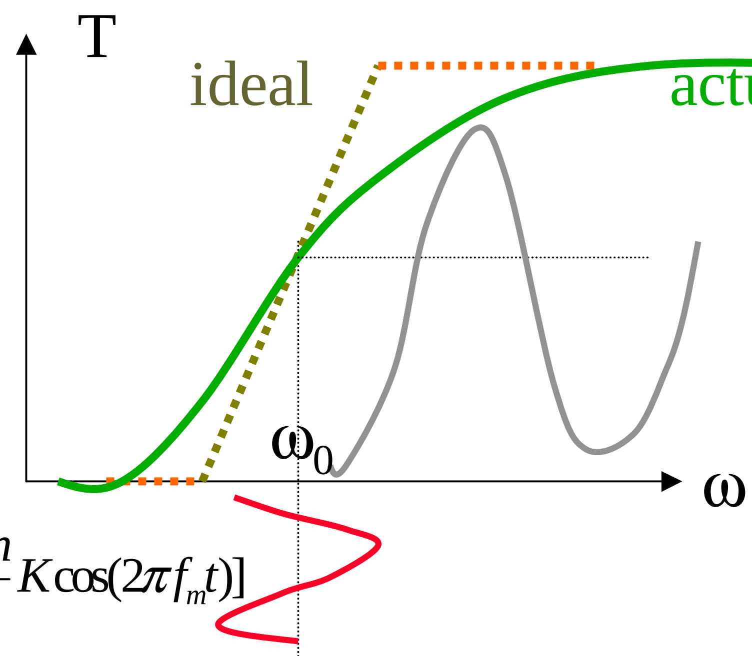
After demodulator and squaring cancellation takes place:



Intermodulation reduced

Developing better demodulator

- Demodulator must simultaneously be linear and broad-band.
- Typically unbalanced Mach-Zehnder is used.

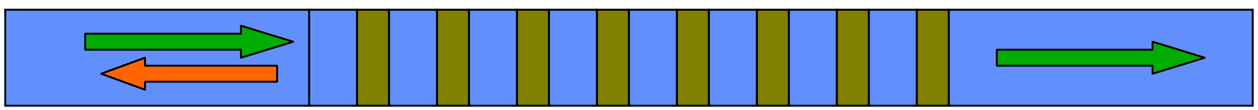


$$I_{out} \sim \sin^2[2\pi \frac{\Delta L}{c}(\omega - \omega_0)] \sim \sin^2[2\pi \frac{\Delta L}{c} \omega_0 \frac{\delta n}{n} K \cos(2\pi f_m t)]$$

- Linearization is achieved electronically

Task: design and implement all-optical linear filter

Instead of Mach-Zehnder we shall use an apodized Bragg grating edge filter specially synthesized for linearity:

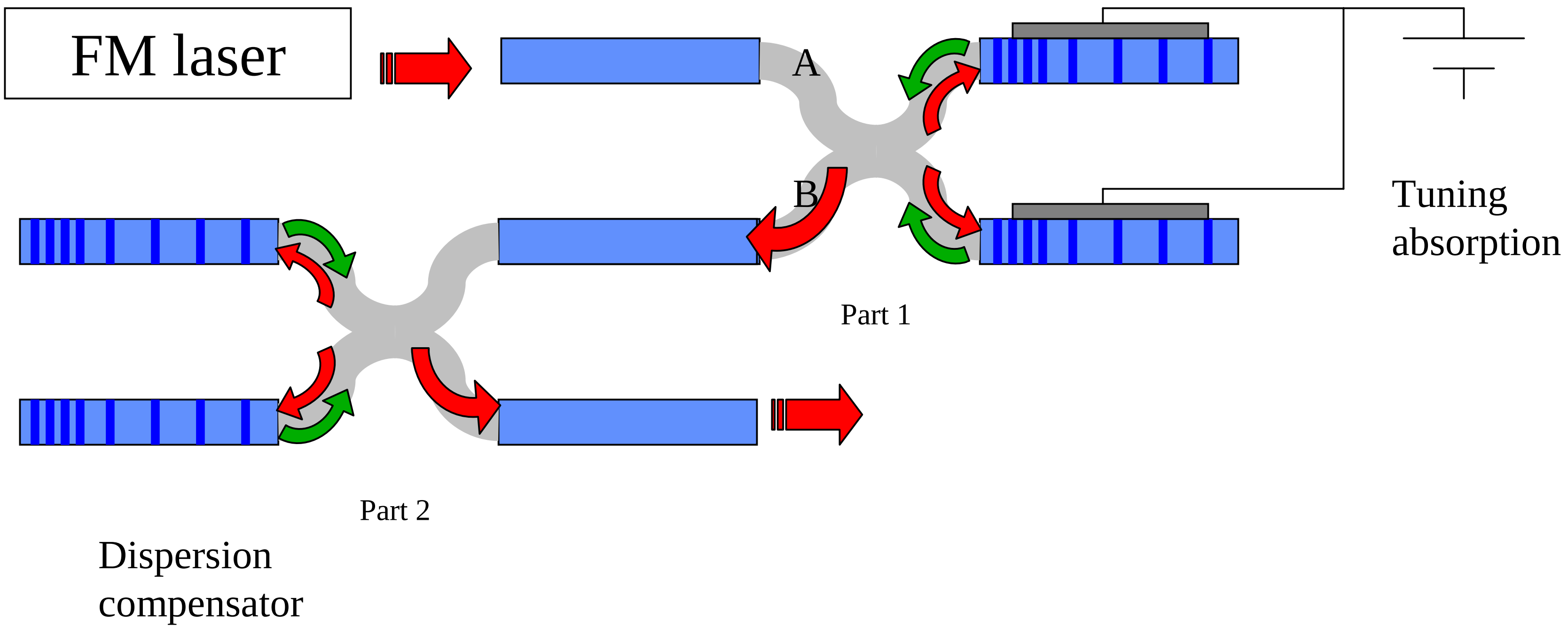


Phase modulation | Intensity modulation

Design is done using iterative method specially developed for the project. This results in phase and amplitude chirped grating.

Proposed integrated linear FM->AM converter

Idea: use linearly chirped grating combined with absorption the light of different frequencies gets reflected at different points thus its absorption varies. We show that one can engineer PERFECTLY linear demodulator.



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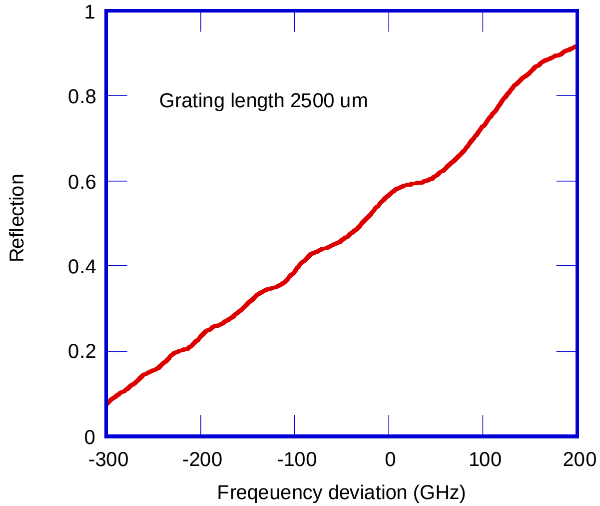
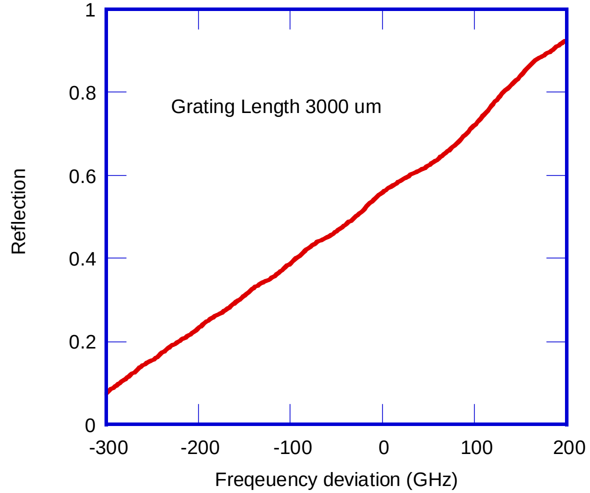
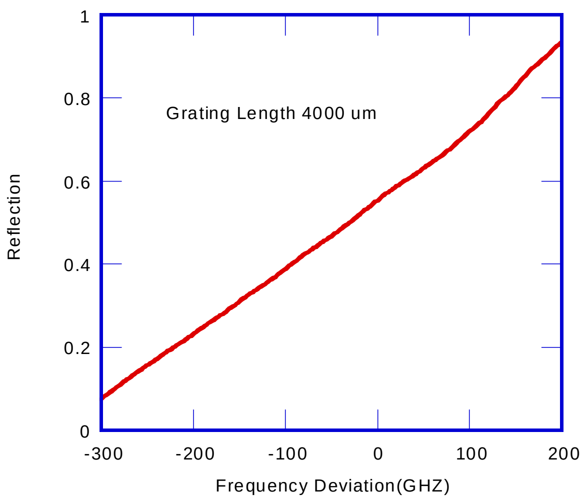
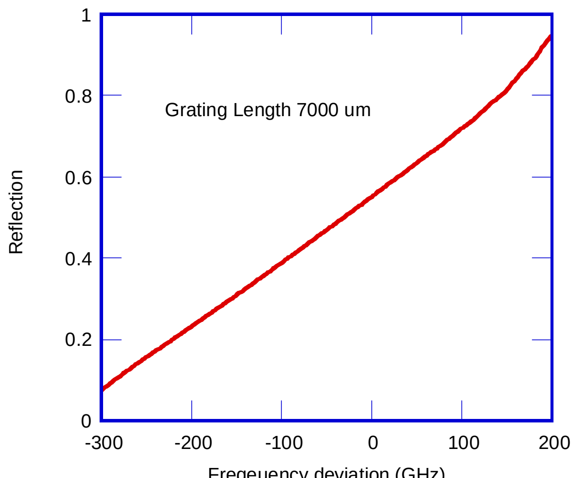
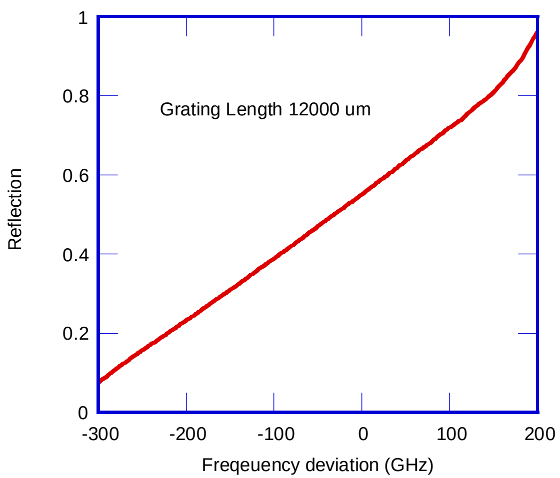
Performance of the proposed demodulator



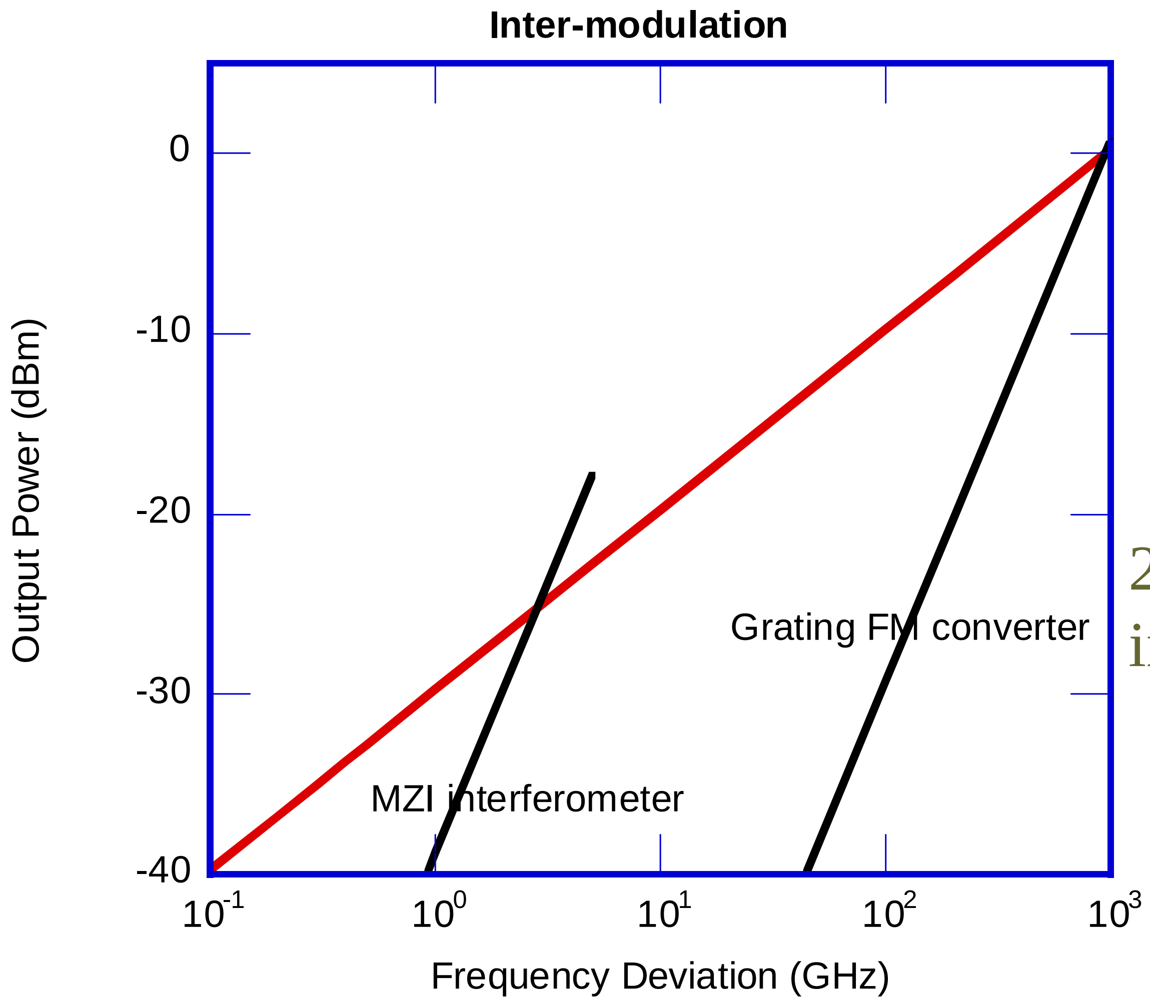








Improvement in the Intermodulation Product ($2f_2$-f_1)



25 dB improvement in dynamic range

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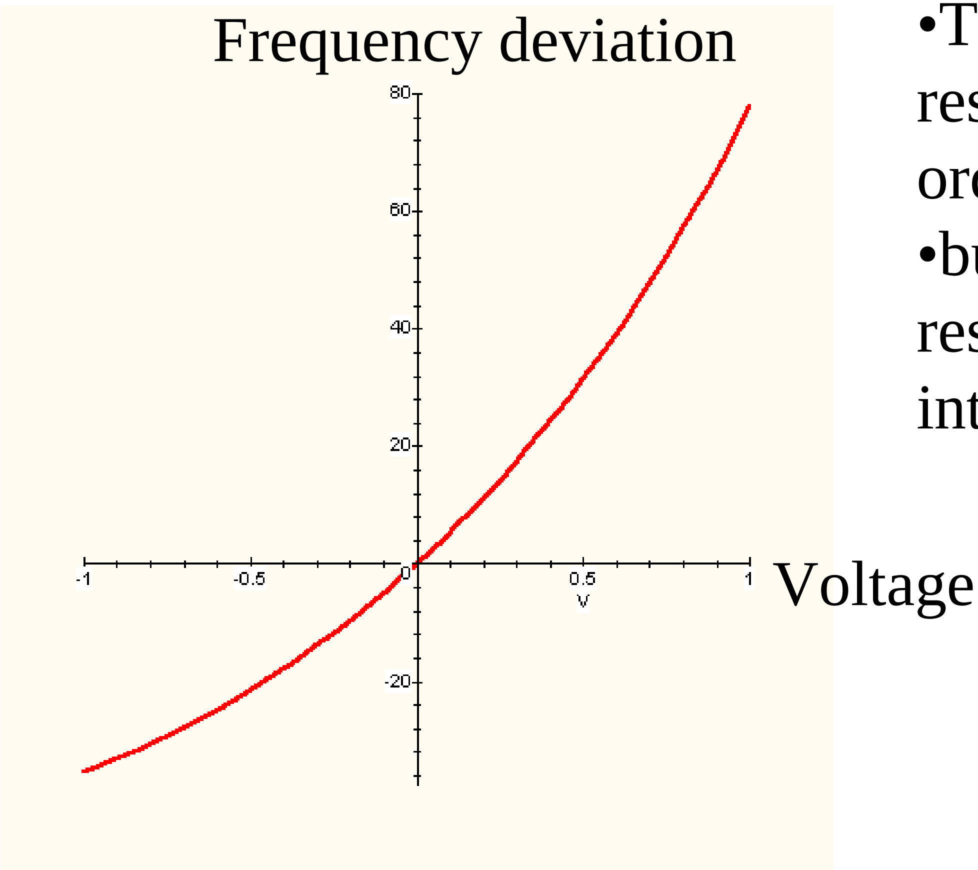
More work on demodulator:

- Refine the iterative program to allow simultaneous chirp in amplitude, phase and spatial frequency
- Consider the demodualtion in fiber grating
- Consider nonlinearity in EA modulator and design the chirped Bragg filter to compensate it.
- Consider the ways for tuning the demodulator absorption: strain, temperature etc.
- Separately - develop a "truly linear" electrooptic modulator based on grating+absorption

Nonlinearity in QCSE Phase Modulator



•This nonlinearity is mostly responsible for the second order distortion

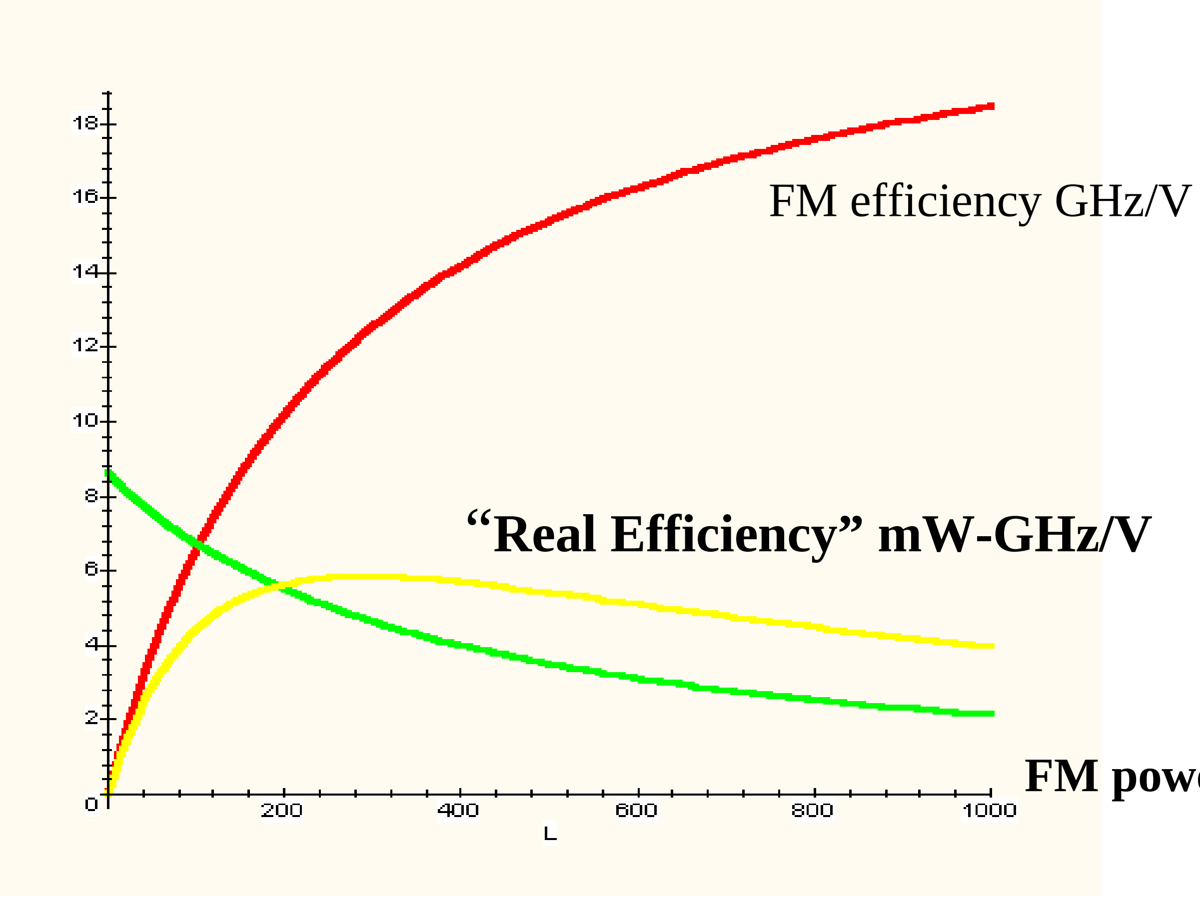
•but the third-order effect, responsible for the intermodulation is also there

Next Step: Combine the QCSE modulator with Bragg demodulator to compensate the distortion

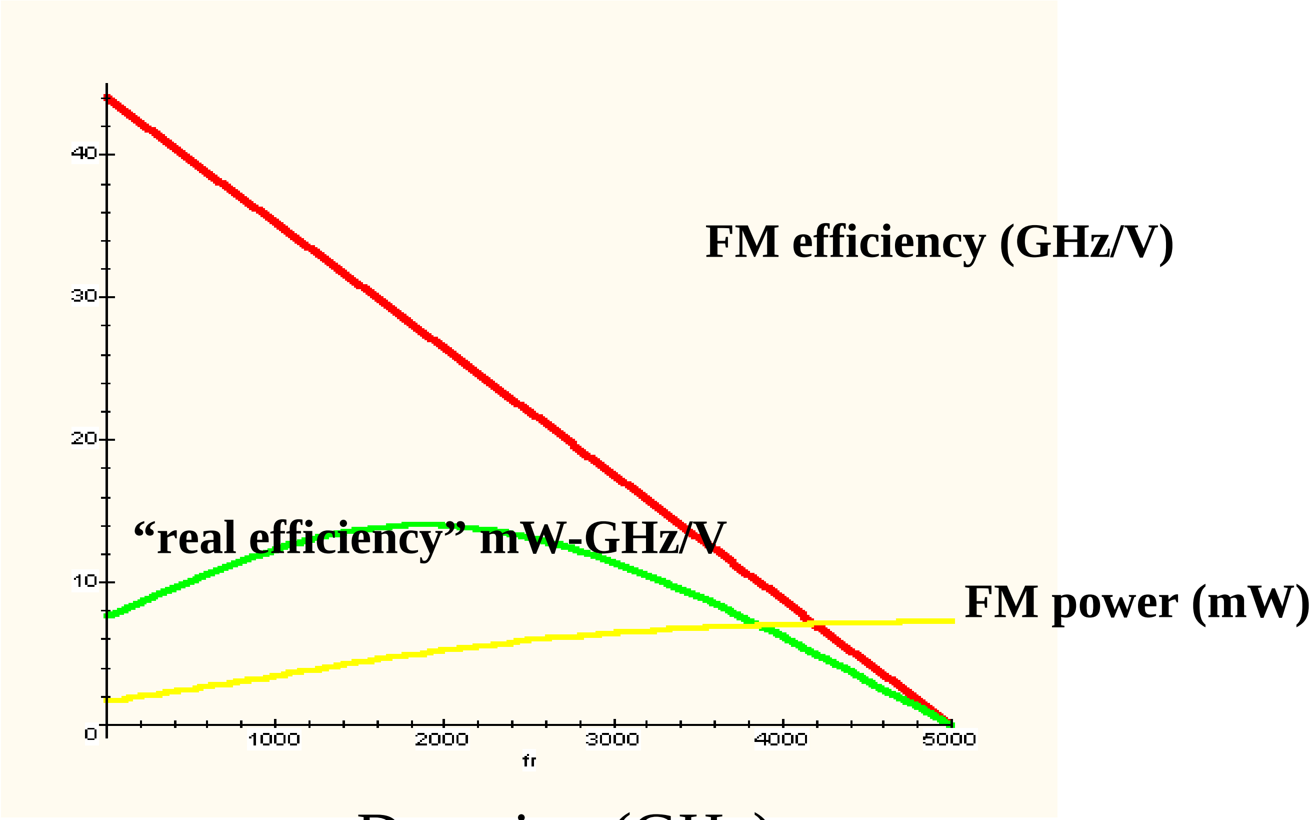
Optimization of detuning and length of QCSE modulator:

- Increasing the modulator length improves the FM efficiency, but reduces optical power due to absorption
- Reducing the detuning has a similar effect
- Optimization had been performed

Optimization of length



Optimization of Detuning



Detuning (GHz)

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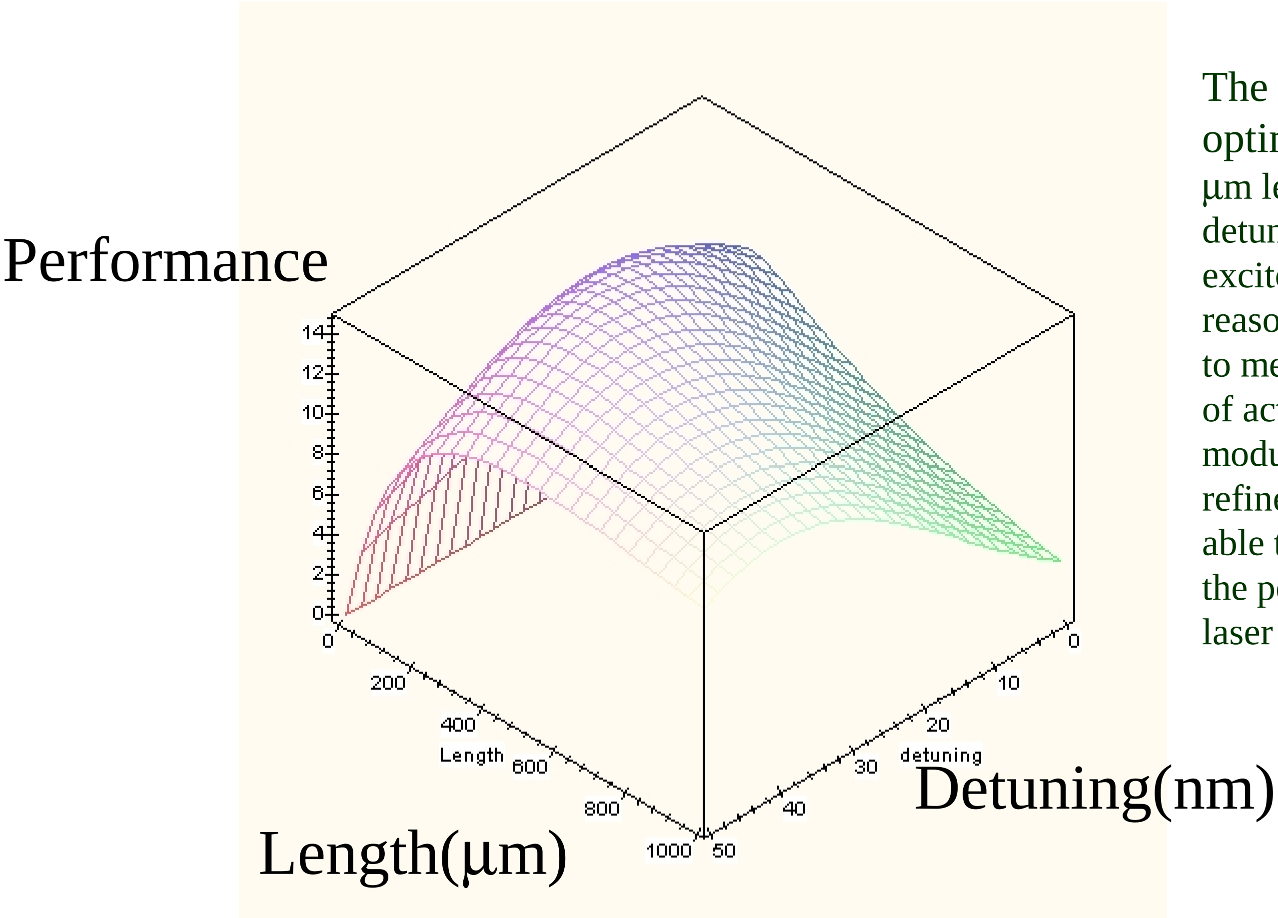
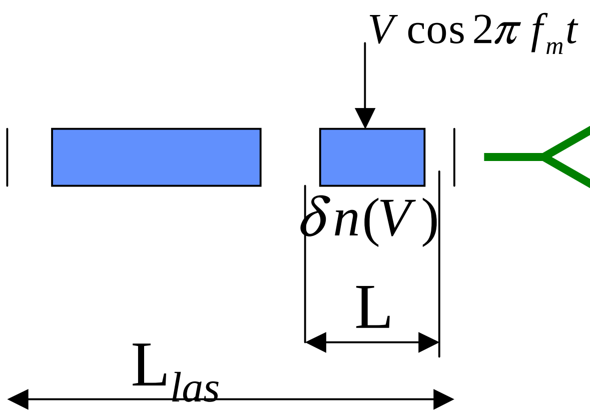
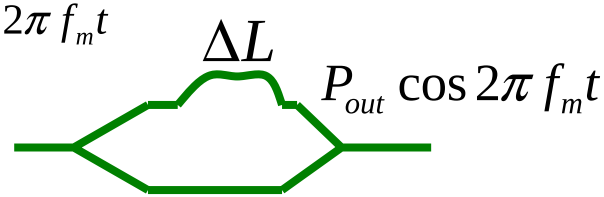
Optimization of total performance

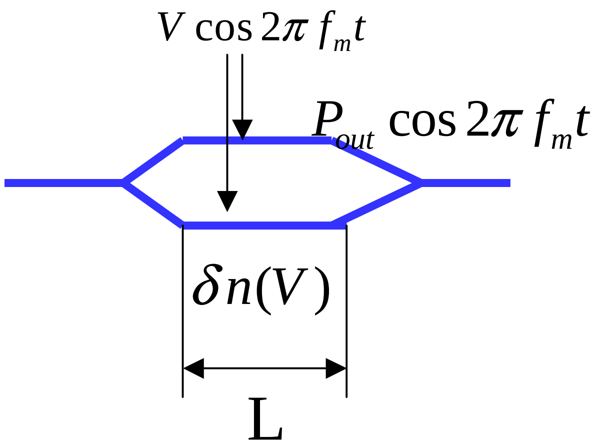


The results of optimisation - ~400 μm length and 35nm detuning from the exciton peak are quite reasonable, but we need to measure the response of actual QCSE modulator in order to refine the model and be able to precisely predict the performance of FM laser

Comparing
FM laser and EOM







Efficiency:

$$G_{FM} = \frac{\partial P_{out}}{\partial V} = \frac{L f_0}{L_{las} f_m n_0}\frac{\partial n}{\partial V} P_{in}$$

Small L~250µm is OK,

insertion loss inside cavity -no problem -multiple QW's with QCSE

can be used -dn/dV~$10^{-3}V^{-1}$,
G_{FM}~$3P_{in}$/V @ 10GHz

$$G_{EOM} = \frac{\partial P_{out}}{\partial V} = \frac{2\pi f_0 L}{c}\frac{\partial n}{\partial V} P_{in}$$

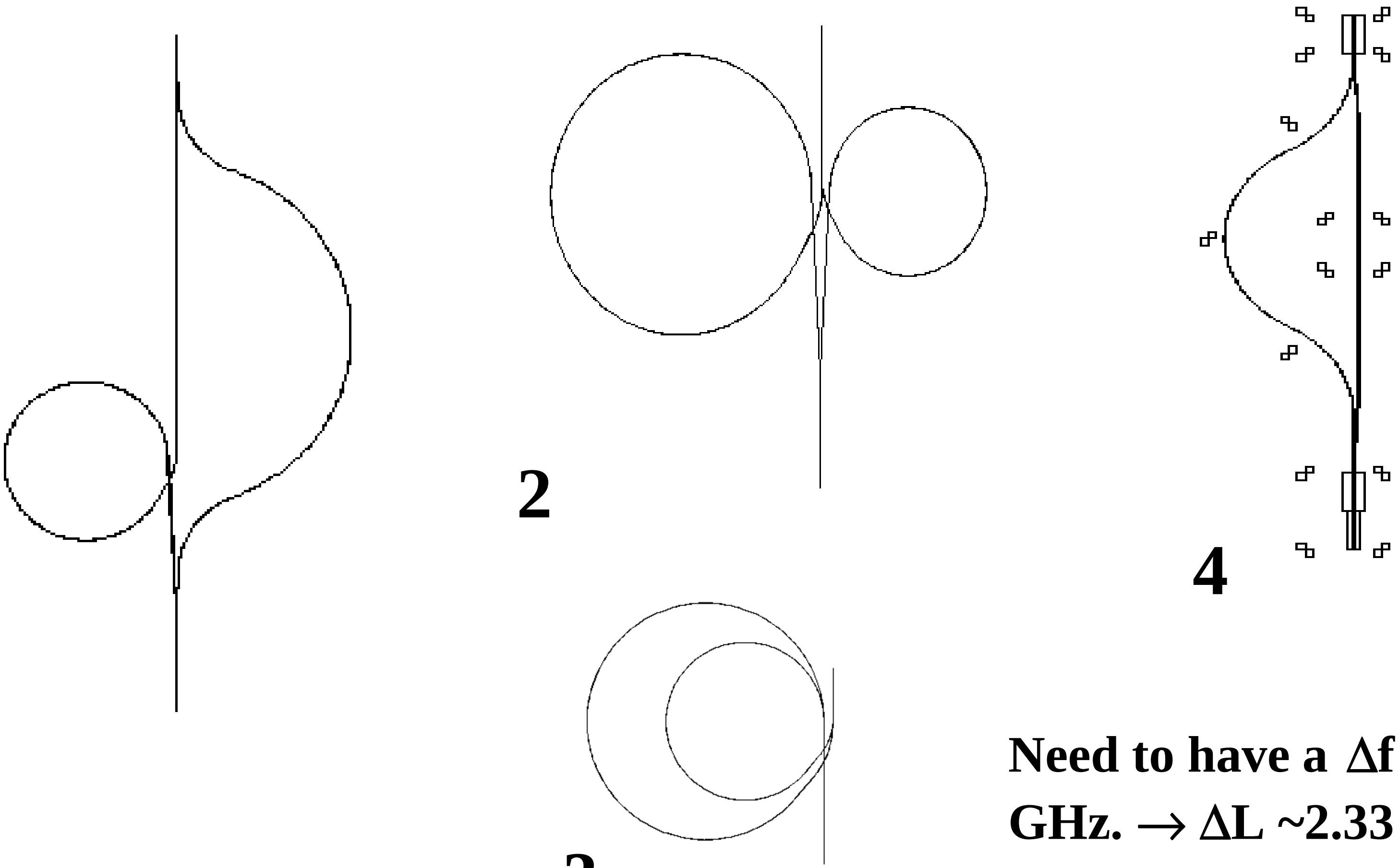
L is long ~ 3cm,
insertion loss -big problem
$LiNbO_3$ - dn/dV<$10^{-5}V^{-1}$,
G_{EOM}~0.3 P_{in}/V @ 10GHz

FM is at least 10 times more efficient than the AM

What is next?

- The dynamic model of FM laser developed and tested
- QCSE modulator and integrated FM-AM converter are modeled and their effects on the dynamic range are studied
- Rough optimization of modulator parameters is done
- NEXT: measurements of the real parameters of laser and modulator in order to fit them into the model
- MORE interaction with experiment
- Detailed study of instability and ways to avoid it (we have some ideas!!!)

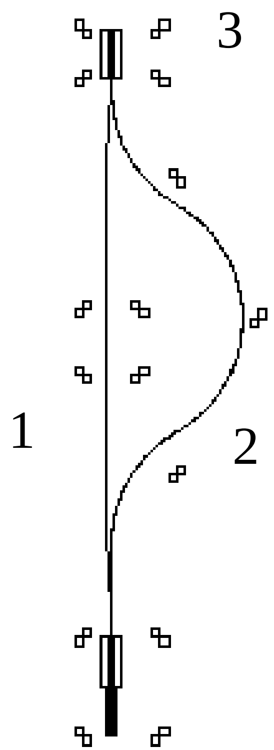
Waveguide Design

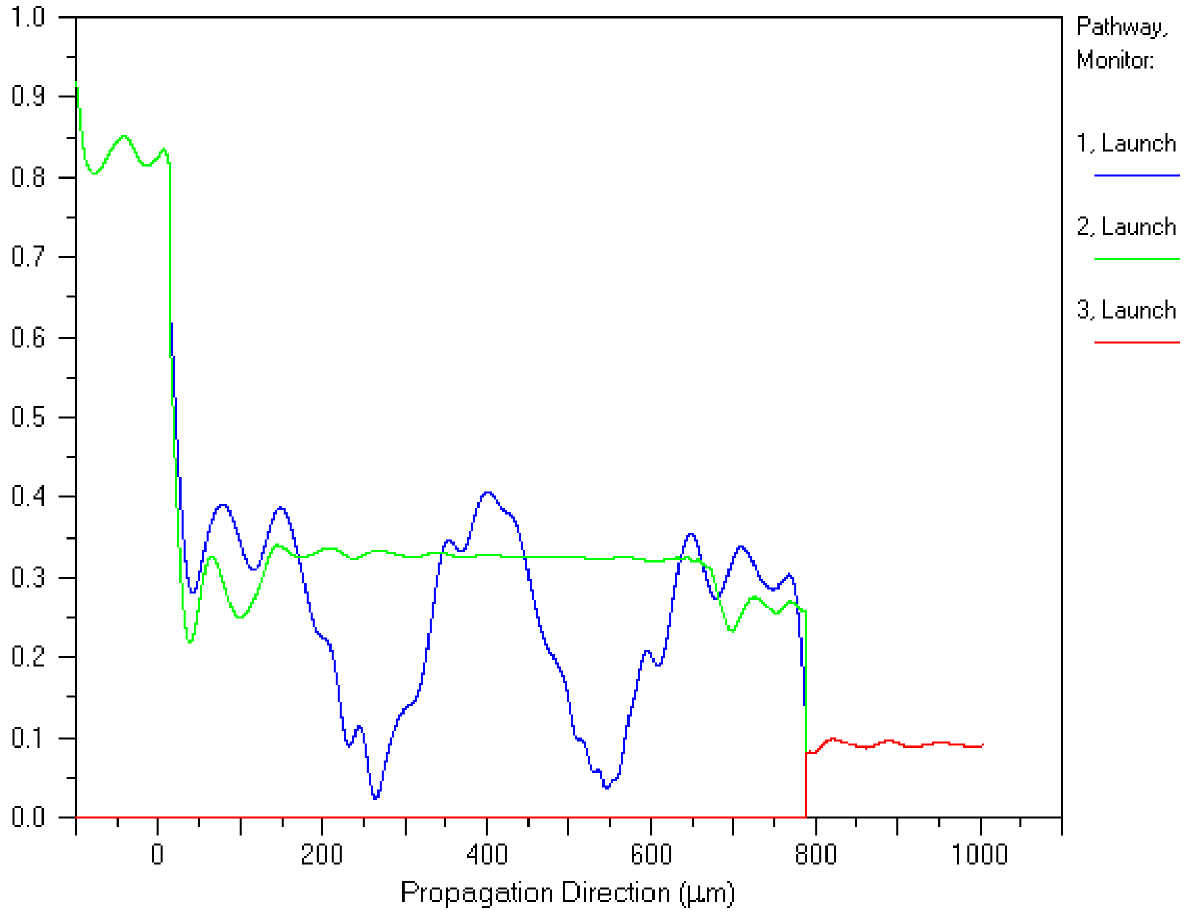


1 2 3 4

Need to have a $\Delta f \sim 40$ GHz. $\rightarrow \Delta L \sim 2.33$ mm

Balancing Bending and Propagation Losses





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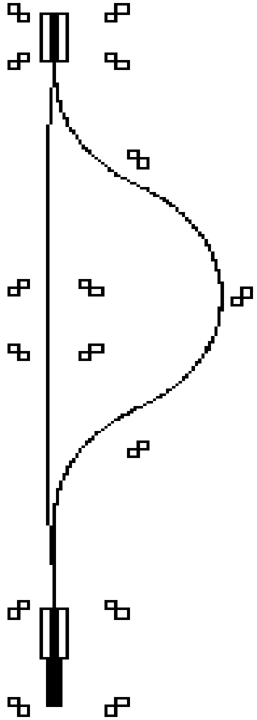
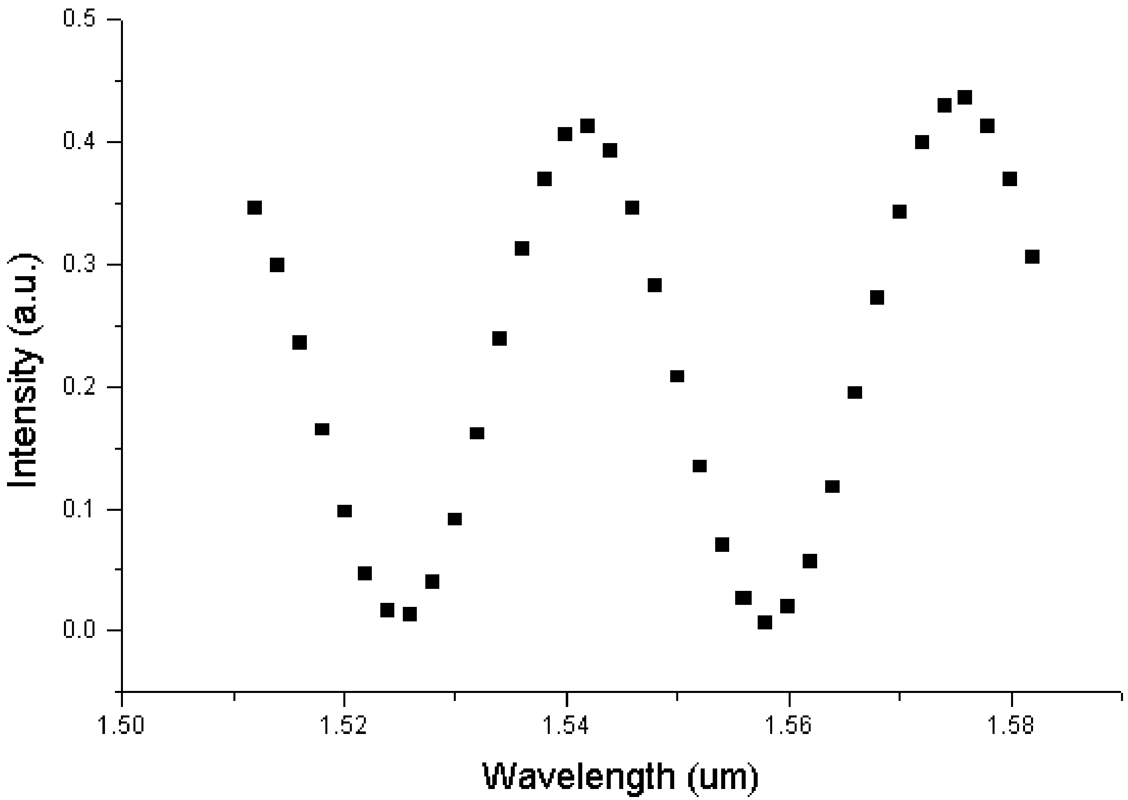
Obtain Demodulators with Different Slops

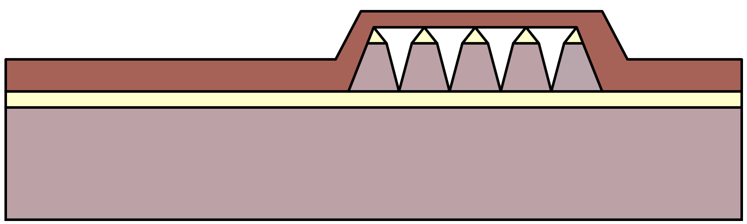




Fabrication Processes

1. Grow bottom waveguide & grating layers

2. Grating fab. & oxide cover

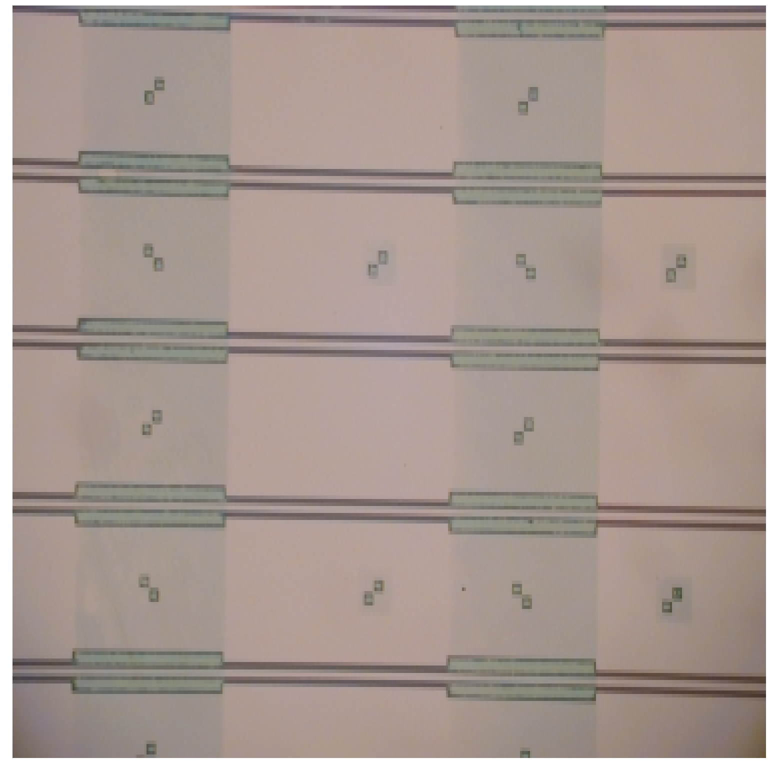


1.3Q

InP

Oxide

3. Oxide patterning for selective area growth



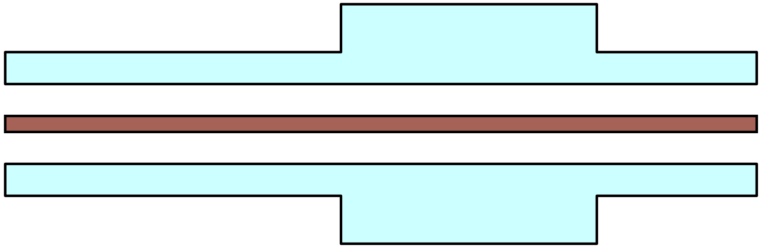
Fabrication Processes

4. Selective area growth

6. SI InP regrowth & P-cap regrowth

7. Metalization, patterning, and section isolation

5. Waveguide etch



1.3Q

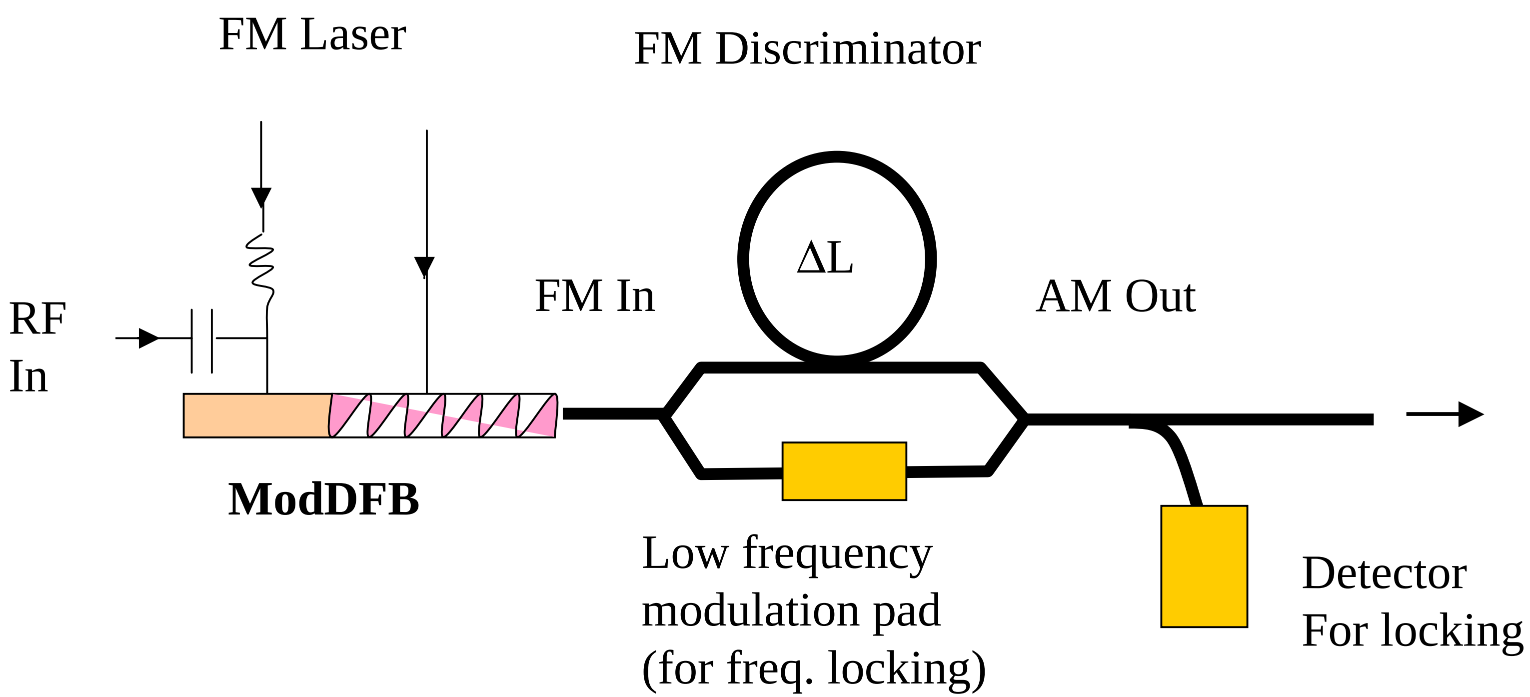
InP

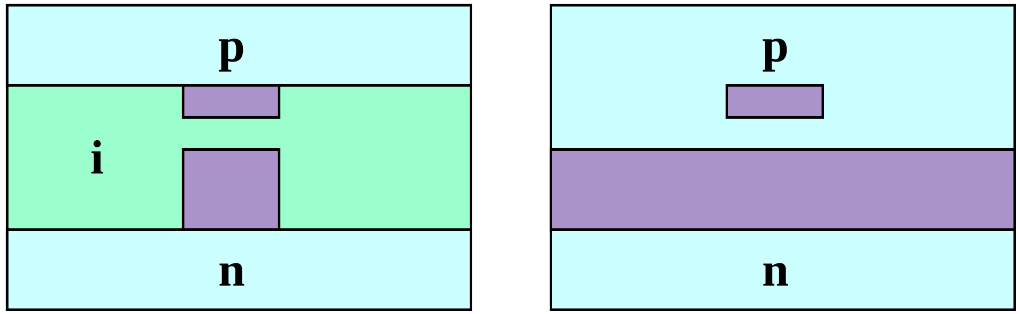
Oxide

Oxide removed

Cladding & Gain materials

Integration Designs





KEY MILESTONE NEXT YEAR

1. **Design and fabrication of high efficiency FM lasers .**
2. **Integration of FM lasers and demodulator .**
3. **Measurements of group velocity in photonic gap structures.**
4. **Fabrication and testing of lithium niobate photonic gap electro-optic modulators**